FREE CONVECTION VELOCITY MEASUREMENTS
BY THE USE OF NEUTRAL DENSITY PARTICLES

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SUMMARY

A velocity measurement technique for measuring velocities using small, hollow glass spheres was developed for both steady and transient free convective flow of water. The microspheres suspended in the water were illuminated by a narrow beam of light and photographed at right angles to the beam of light by the use of a camera-shutter system as they moved with the free convective water currents. A shutter wheel containing equally-spaced, tapered slits was rotated at a constant speed in front of the lens of the camera. The particle trajectories appeared as a series of short streaks on the film. The velocities were determined by measurements of streak lengths on a lithofilm print and a knowledge of the exposure time. Velocity corrections were made for distortion due to light refraction.

Optimum photographic conditions were established by the variation of the important parameters: light intensity, width of light beam, particle density, exposure rate, and film speed. The best combination of test conditions from the standpoint of photographs from which velocities could be easily measured was found to be the Kodak Tri-X film using a 1/4-inch light box slit with four lamps, a particle density of 1.92×10^5 particles per cubic foot of water, and an exposure rate of 0.5 exposures per second.

NOMENCLATURE

Symbol		Units
a,b,c	vertical distances	inches
D	distance from inside surface of the glass to position in tank where pictures were taken	inches
d	depth of field	inches
m	magnification factor	dimensionless
$\overline{OC}$	distance from center of camera lens to optical center of the position where picture was taken	inches
p	distance of the apparent image from the center of the lens	inches
R_A, R_B	radii from the apparent position of a particle to the optical center of the picture	inches
R_h	hydraulic radius of semicircular tube	inches
$\bar{R}_p$	$1/2\ (R_A + R_B)$	inches
s	scale factor	dimensionless
t	thickness of glass	inches
V_{true}	true particle velocity	in./sec
x	distance from apparent image position to inside edge of glass	inches
z'	radius of circle of confusion	inches

Greek Letters

δ	distance between apparent particle position and actual particle position	inches

θ_A, θ_B	angles measured at optical center between R_A, R_B and a horizontal line	radians
μ_w	coefficient of light refraction in water	dimensionless
μ_g	coefficient of light refraction in glass	dimensionless
ρ	radius of camera opening	inches
$\Delta\tau$	time interval during which particle moved from point A to point B	seconds
$\Phi_{1,2,3,4}$	angles measured from the horizontal	radians

CHAPTER I

INTRODUCTION

The purpose of this study was to develop a photographic technique for measuring velocities of water flow, especially for steady and transient free convective flow in a tank. A system consisting of a narrow light beam and camera-shutter system was devised to photograph the movement of small glass spheres suspended in the water. A wheel containing four equally-spaced, radial slits and driven by a constant-speed motor is rotated in front of the lens of a 4 by 5 press-type camera, thus intermittently exposing the film to the light reflected from the glass particles. The light beam is provided by a light box consisting of high intensity lamps and a lens-slit system which produces a narrow beam of light with a small angle of divergence. The light box is placed on top of the tank so that the beam is directed normal to the water surface. The light reflected at right angles by the glass particles passes through a glass side of the tank into the camera. The tank used in this experiment was two feet square by three feet high with glass on two opposite sides and heater plates on the other two sides and the bottom to provide a transient driving force for the convective currents. The velocity of a glass sphere is determined from a measurement of its trajectory length on a high contrast enlarged 7 1/2 by 9 1/2 print made from the 3 3/4 by 4 3/4 negative and a knowledge of the exposure rate. The exposure rate is determined from the speed of rotation of the gear-motor turning the shutter wheel. Correction of the velocity for distortion due to refraction in the water is made. A sample calculation is shown in Appendix A.

Before choosing a method for measuring velocities in free convective flow, it was necessary to consider different types of velocity measuring devices. The measurement of velocities of fluids presents a problem not generally associated with the velocity measurement of a solid body. Fluids are not usually visible in such a manner as to enable the determination of velocity directly from measurements of time and space. Some velocity measuring instrument or technique must therefore be employed. Many velocity measuring devices practical for use in many applications are impractical for use in experiments of this type. Venturi meters, flow nozzles and orifices are restricted in use to measuring average velocities in closed conduits. Pitot tubes and hot-wire anemometers are frequently used to measure local velocities of fluids; however, low velocity heads viscous effects and small pressure differences encountered in free convective flow limit the usefulness of these intruments. In addition, the sensing elements of both anemometers and pitot tubes have directional properties. Thus the orientation of these elements to give the desired velocity reading would be difficult, if not impossible, in this study due to the transient nature of the flow. Generally, any velocity measuring device would present an obstruction to the flow. Also, the transient nature of the flow would require a larger number of simultaneous velocity measurements than could be achieved by any measuring device.

Since fluid velocity measuring devices are inadequate for use in this study, another velocity measuring technique must be employed. The method of measuring velocities by photographing neutral density particles suspended in a fluid has proved to be a successful technique in various investigations such as fluid flow in furnaces, water tunnels and combustion chambers and free convective flow of air.

One of the earliest applications of the photographic technique was by Fage and Preston[1] in 1941 for a quantitative study of flow around scale models of streamlined bodies of revolution suspended in the test section of a water tunnel. To trace the flow of the water, tiny particles in the form of fine aluminum powder with an average diameter of about 0.0015 inch were suspended in the water. A 1000-watt projector lamp and a lens were used to produce a narrow beam of light to illuminate the area around the model in the test section. Instead of using a camera to photograph the particle movement, a fluid-motion microscope with an interrupter was used. A fluid motion microscope is an instrument which allows the movements of small particles in a bright light to be studied and measured. It is used for study of flow in which the suspended particles are too small to be seen by the naked eye, but which can be observed under the magnification of a microscope. The interrupter is a small disk containing uniformly-spaced radial teeth turning at a constant speed in front of the objective of the microscope. By placing a photographic plate in place of the eye piece of the microscope, the particle speed was determined by measuring its length on the photograph and knowing the exposure time.

In 1949 Howes and Philip[2] developed a system to study flow patterns, mixing rates, and velocities in an open-hearth furnace. Water, used as the test fluid, was circulated through a scale model of the furnace. Two light sources were used: a lamp box for flow visualization and a flash discharge tube for measuring velocities. The lamp box contained a two-kilowatt lamp with an adjustable reflector and an air ventilating system and provided a light that was useful for flow visualization but not bright enough for photographic purposes. A short exposure time of 1/100 to 1/200 second produced optimum streak lengths of air bubbles used as tracers of the fast-moving flow. A special flash discharge tube was developed which produced a bright sheet of light over a variable exposure time of 1/125 to 1/2000 second. A rough estimate of the general magnitude of the velocities was accomplished by measuring the tracer lengths on the photographs and calibrating the flash tube so that the exposure rate would be known. The direction of the velocity was also determined from the flash discharge tube since the flash reached its highest intensity fast and tapered off slowly, thus causing the head of the bubble trajectory to appear dimmer than the tail. Since flow in furnaces is three-dimensional, a three-dimensional study was made by rotating the camera and light beam through 90 degrees and taking a photograph of the transverse flow.

Winter and Deterding[3] in 1955 studied the flow in gas turbines and boilers during continuous combustion. A hydraulic system containing a scale model was used to simulate the gas flow. The method of measuring velocities in the test section was patterned after the method used by Howes and Philips. However, an improvement was made in the technique by the use of neutral density polystyrene particles rather than air bubbles as tracers of the flow in the system.

In 1959 Yerman, et al.[4] made a study of a technique for a quantitative, three-dimentional flow visualization. A water recirculating system containing a straight section of transparent duct of rectangular cross-section was used. A mercury capillary lamp operating on 1000 watts in conjunction with a condenser lens produced a collimated beam of light which could be moved vertically in front of one side of the transparent duct, thus brightly illuminating any horizontal plane desired. A camera placed at right angles to the light beam was used to photograph the movement of small spherical polystyrene particles suspended in the water. A light beam chopper consisting of a small metal disk turned by an induction motor in front of the light beam caused the particles to appear as trajectories on the photograph. Velocities could be determined by knowing exposure rate and trajectory length. No provision was made for determining the direction of the velocity from the photograph.

Van Meer and Vermij[5] in 1961 also made a study in flow visualization and velocity measurement for three-dimensional flow. Color was used as an indication of the third dimension. Opaque polystyrene spheres were placed in the water of a forced flow, recirculatory system. The special lighting equipment consisted of a point light source placed before a parabolic mirror. The parallel light beam produced then passed through a multi-color filter which split the light into parallel bands of colored light. A camera containing highly sensitive color film was positioned perpendicular to the light source. A polystyrene sphere passed through the test section in such a manner that it traversed the color band and appeared on the film in a series of different colors.

Thus the velocity of the particles moving toward or away from the camera was determined by knowing the time the particle remained in each color band. The light beam was interrupted and the particle velocities in a plane perpendicular to the camera lens were determined by the same method used by Yerman, et al.

Eichhorn[6] in 1962 developed a method for measuring velocities of free convective flow of air. An experimental setup was devised in order to determine free convective velocity profiles about a heated, uniform temperature, vertical flat plate. Zinc stearate dust particles, which were injected into the flow, were illuminated in a test section by a mercury-arc, point source lamp with a lens system. A Prakiflex 35 mm camera with a special lens assembly which had a short depth of field made it possible to achieve pointwise measurement of the particles. Particle velocities were determined in a manner similar to that used by Yerman,et al.

The velocity measuring technique used in each of these studies consisted of suspending particles in a fluid and photographing their movement using a camera-shutter system in conjunction with a light source producing a narrow beam. Various types of lighting equipment, cameras, films, shutter systems, and flow tracers were successfully used in the various applications. The basis of the technique discussed in this thesis was derived from these previous experiments. Several changes to satisfy the application and some improvements over previous methods were made. The rotating wheel used to intermittently expose the film was placed in front of the camera rather than in front of the light source, as had previously been done, mainly due to convenience in setting up the apparatus. No provision had previously been made for determining the direction of the moving particle from the photograph except in the case of the flash discharge tube used first by Howes and Philips. Equally-spaced, tapered slits were cut in the rotating wheel used in this experiment so that the particle trajectories would appear on the film brighter at the head than at the tail. Many types of neutral density particles were considered before tiny, hollow glass spheres were chosen. Bailey[7] of the Martin Company used these particles to study convection patterns in water to simulate nuclear heating of liquid hydrogen. However, these particles have not been previously used for velocity measurement purposes. They are outstanding tracers of the flow since they are spherical in shape, reflect light well at right angles, and have a density close to that of water. In developing the film a high contrast print was made of the 3 3/4 by 4 3/4 negative and enlarged to 7 1/2 by 9 1/2 print. From this print it was easy to trace and measure a series of trajectories of a single particle.

The velocity measuring technique developed in this thesis to study free convective flow of water could be used for other two-dimensional applications using water as a fluid. Velocities as much as five or six times larger than those in the range of 0 to 15 in./min measured in this experiment could be determined using the available equipment. This is possible since the number of exposures per second of the particles on the film can be varied from approximately 1/2 exp/sec* to 3 1/2 exp/sec by changing the gear-motor used to drive the rotating shutter

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* Exposure is abbreviated as "exp".

wheel. For an application requiring a higher light intensity than that used here, the lamps in the light box could be operated at input voltages higher than 120, thus greatly increasing the light intensity.

CHAPTER II

EQUIPMENT

A photographic system consisting of a light box and camera-shutter system was used to determine velocities in free convective flow. The flow was observed in water contained in a tank two feet square by three feet high with individually controlled heater plates on its bottom and two opposite sides. Neutral density particles in the form of hollow, glass microspheres were placed in the water to provide tracers of the flow that could be photographed. Particles in only a small region of the tank near its center were illuminated by a narrow light beam emitted from a light box. The light box contained four 1,000 watt, iodine quartz lamps, providing a line source of light; a lens at its focal length from the lamps; and a slit to produce a light beam having a very small angle of divergence. The light box was placed on top the tank so that the light beam was directed downward in the center of the tank. A 4 by 5 Crown Graphic press-type camera was placed in a camera box which was mounted on a platform that could be moved vertically by sliding it in the slit of a camera stand. The camera was aimed perpendicular to one of the two glass sides of the tank so that it received light reflected at right angles by the glass particles in the water. Pictures of the particles in practically any portion of the illuminated region of the tank could be obtained by moving the camera stand toward or away from the tank, to the left or the right, or by moving the camera box vertically. A shutter system was built to intermittently expose the film to the light reflected by the glass particles so that a particle would appear on the film as a series of tiny trajectories. It consisted of a wheel which was turned at a constant speed in front of the camera lens by a small electric gear-motor. The gear-motor was mounted on a frame which had a vertical adjustment and was positioned on a platform on top the camera box. Four gear-motors of different speeds were used and the shutter wheel contained four equally-spaced, 45-degree tapered slits located near the periphery of the wheel. Six switches to operate the light box fan, the shutter wheel, and each light separately were mounted side by side on the camera box. The entire apparatus is shown in Figure 1.

Light Box

A light box was designed and built to produce a bright, narrow beam of light. The box contains four Sylvania iodine quartz lamps placed in holders end-to-end in a straight line in the center of the light box, a lens to collimate the light, a choice of either a 2, 1/2, or 1/4-inch slit to further collimate the light, and a cooling fan. The box, which was made of 1/2-inch plyboard, was 28 inches by 25 inches by 30 inches long. The dimensions were made larger than would have been necessary for a metal box in order to provide a larger heat transfer surface to prevent overheating of the wood. The inside surface of the box was lined with aluminum foil to further prevent overheating. The cooling fan was a centrifugal fan driven by an electric motor. The fan was mounted on the outside surface of the box and pulled air from the box

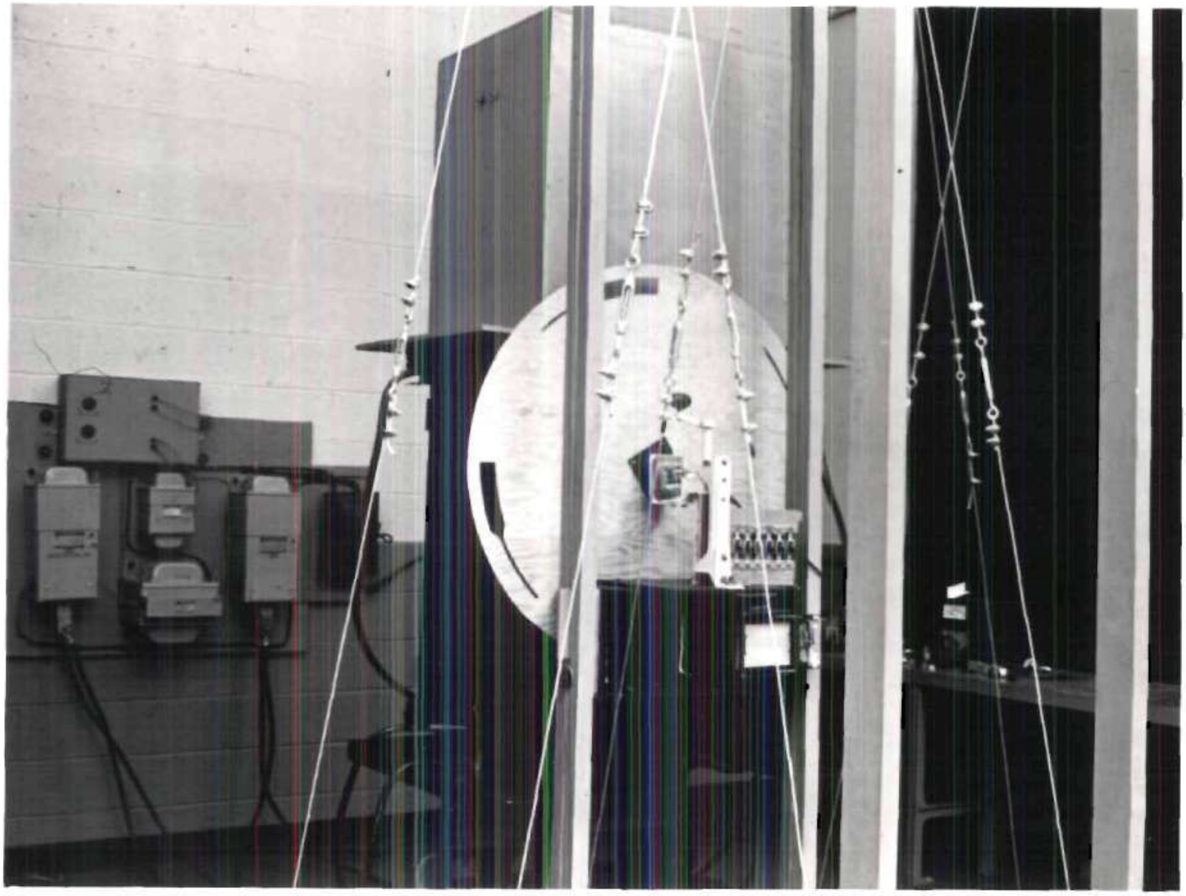

Figure 1. Experiment Equipment.

through holes located near the lights. In order to minimize light reflection from the sides of the box, an inner chamber 2 inches wide by 24 inches long was placed in front of the lens in the center of the box. The chamber, made of 1/4-inch plyboard, was painted black on the inside surface to prevent light reflection. It was possible to close off the end of the chamber to a 1/4-inch or 1/2-inch slit in order to make a narrower light beam.

The Sylvania iodine quartz lamps were rated at 1,000 watts, 19,000 lumens each when operated at 120 volts. It is possible to operate the lamps at higher voltages thus greatly increasing the light intensity. However, the life of the lamp would be reduced. The lens was a cylindrical lens 7 15/16 inches long by 2 1/2 inches wide with a focal length of 2.58 inches. Three lenses were mounted end-to-end in a wooden frame and placed in front of the lamps at approximately the focal distance of a lens. The position of the lens could be adjusted by moving the lens frame in slits in the side of the box.

The light box produced a narrow beam of light 27 inches long with a small angle of divergence of approximately 3.8 degrees. This divergence was due mainly to the low quality of lens used. The width of the beam was controlled by the size of slit used in the end of the inner chamber. The intensity of the light emitted was measured using a light meter. The results for different slits and distances from the box are given in Appendix G.

Two sectional views of the light box are shown in Figures 2 and 3. Figure 2 is a section taken through the center of the box looking from a side. Figure 3 is a section taken through the center

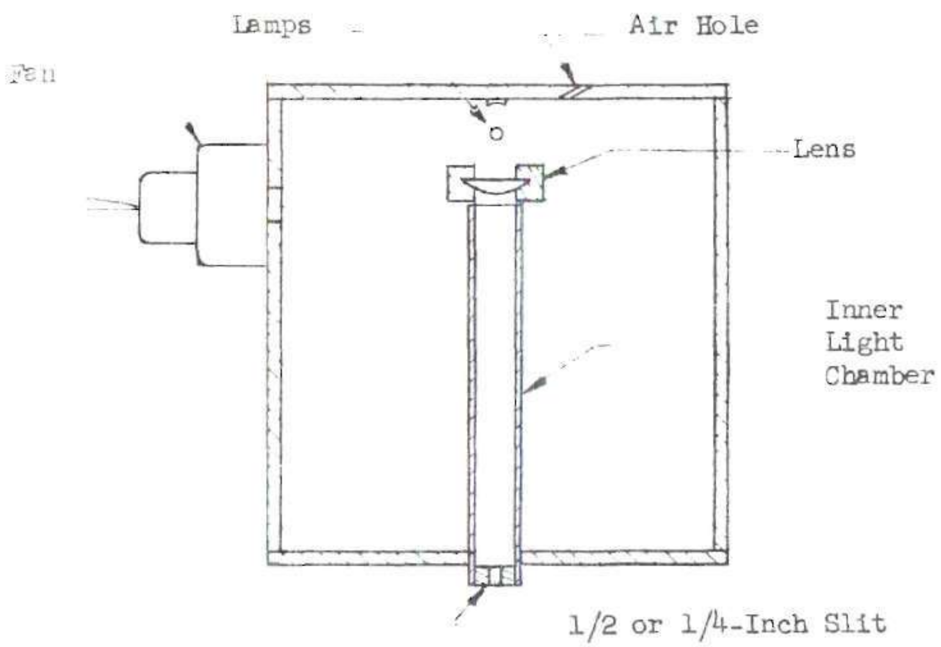

Figure 2. Light Box - Side Sectional View Taken Through the Center.

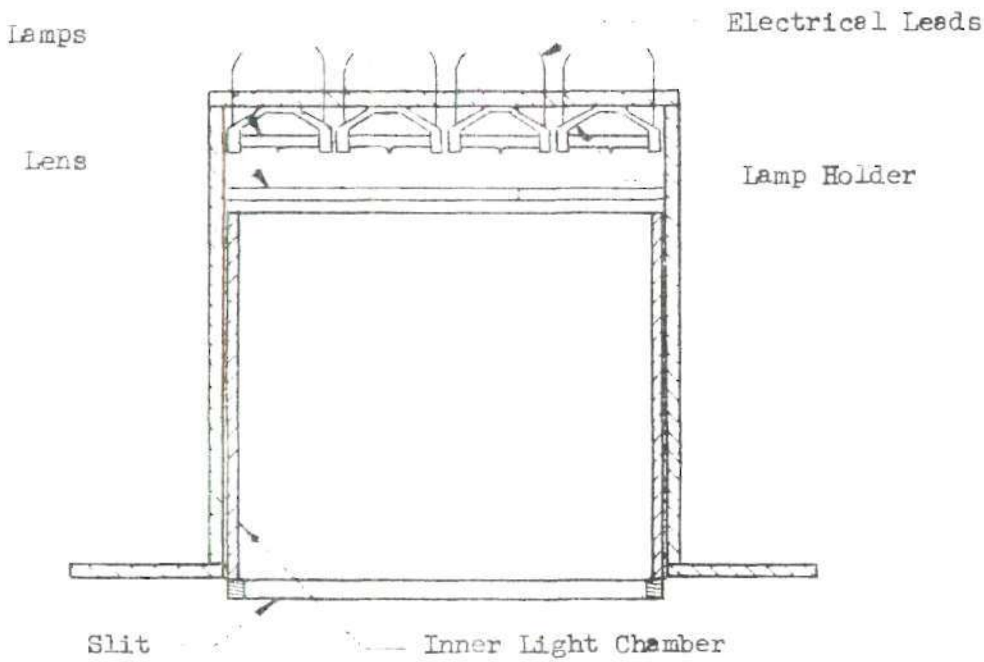

Figure 3. Light Box - Front Sectional View Taken Through the Center.

of the box looking from the front. An external view of the box can be seen in Figure 1.

Camera-Shutter System

The camera used to make all the photographs was a 125 mm 4 by 5 Crown Graphic press-type camera. The shutter of the camera was locked open and a lens aperture of 4.7 was used during the entire experiment. The depth of field calculated in Appendix B was found to be 0.22 inch. The camera was placed in a 1/8-inch plyboard box with a 1 1/2-inch hole in the front so that the camera could look into the glass side of the tank. A polaroid adaptor was available for taking polaroid pictures.

A shutter system was devised to intermittently expose the film so that the particles would appear on the film as a series of trajectories. The system consisted of a shutter wheel turned by one of four constant speed gear-motors in front of the camera lens. The 19-inch-radius shutter wheel was made of 1/4-inch plyboard. It contained four equally spaced circular slits extending over 45 degrees of the wheel. The wheel was designed so that a particle would appear on the film the same amount of time it did not appear. Each slit was 1 1/2 inches wide on the leading half of the slit tapering down to 1/4 inch for the trailing half. The slit was tapered to give a direction to the particle trajectory. The wider leading half of the slit permitted more light to reach the film than the narrow trailing half. As a result, the particle trajectory appeared brighter on the end toward which the particle was moving. A diagram of the wheel is shown in Figure 4.

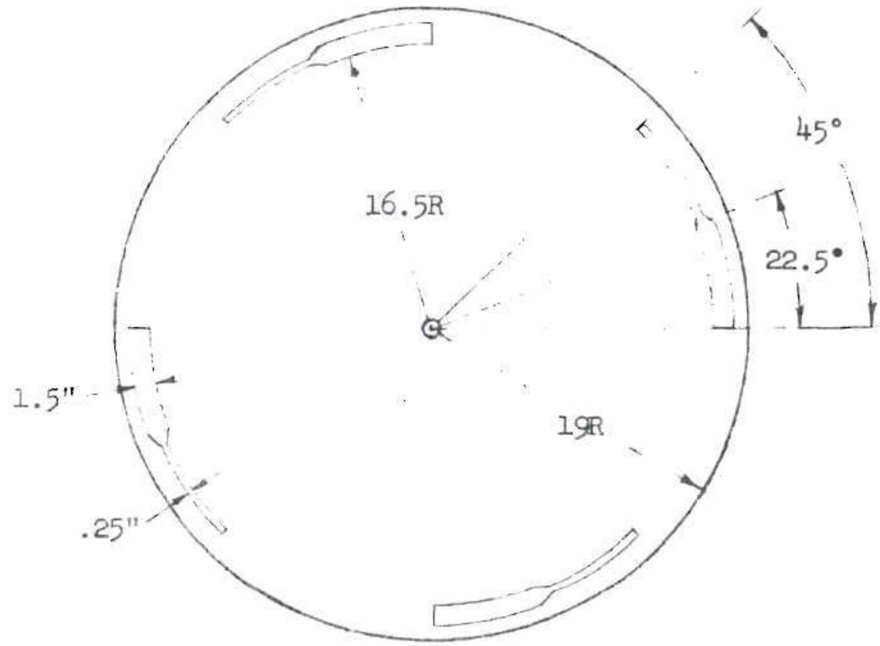

Figure 4. Shutter Wheel.

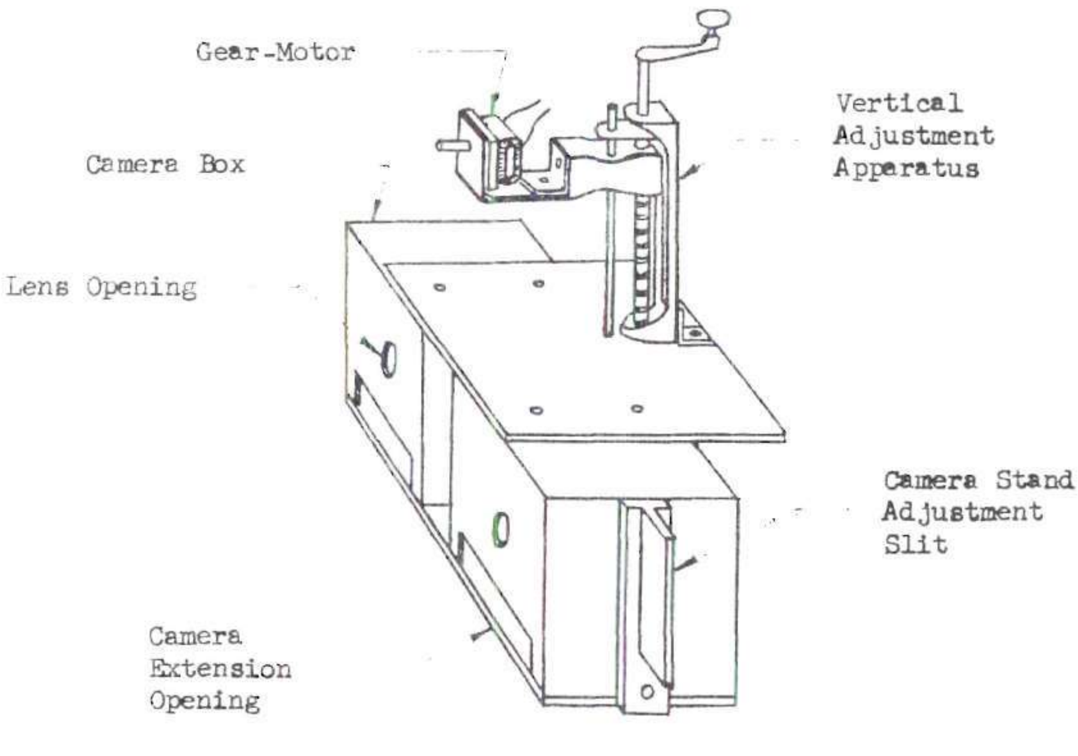

Figure 5. Camera - Shutter System.

The gear-motors used to turn the wheel were continuous duty, two-pole, skeleton-type, shaded pole motors. The gear-motors with speed of 8, 18, and 28 rpm were rated at 1/250 hp and the 50 rpm gear-motor was rated at 1/70 hp output when operated on 115 volts input voltage. Four different speed gear-motors were used to provide different exposure rates. A calibration of the gear-motors is given in Appendix B. A diagram of the camera-shutter system with the shutter wheel removed is shown in Figure 5.

Tank

The tank used to observe and photograph free convective flow of water was two feet square on a side and three feet high. Two sides of the tank were 3/8-inch plate glass while the other two sides and the bottom were 3/4-inch plyboard with stainless steel heater plates bonded to the inside surfaces. When a high electric current was passed through the plates, resistance heat produced convective currents in the water. The tank was designed in this manner so that the flow would be virtually two-dimensional for laminar flow near the heated sides of the tank. Convective currents due to side heating only, bottom heating only, or both together could be produced. The capacity of the tank was approximately 90 gallons.

Selection and Description of Particles

In attempts to visualize a flow field or to develop a velocity measuring technique, there have previously been many types of tracers added to fluids. One of the oldest means of flow visualization was accomplished by injecting dye or smoke into the fluid. However, it was difficult to measure velocities using that method. There have been many types of solid particles used as flow tracers, such as aluminum, iron ore, Bakelite, polystyrene and polyethylene particles, zinc stearate dust particles and air bubbles. The aluminum, iron ore, and Bakelite introduced large gravitational errors in tracing flow paths and were only average light reflectors. Air bubbles were much too light for tracing water flow and were difficult to inject into the flow stream. Spherical polystyrene particles proved to be good tracers of water flow because their density was very close to that of water.

In selecting the type of particles to be used, the following desirable properties were considered:

1. The particles should be spherical in shape. This is to prevent any unbalanced forces on the particles or any peculiar movements due to center of gravity shifts.

2. Their density should be close to that of water so that they will follow a pathline and will remain suspended in the water for a long period of time.

3. They should be small enough to follow the flow in fine detail, yet large enough to be seen without magnification so that they could be used for flow visualization purposes as well as for velocity measurements.

4. They should have the optical property of high reflectivity of the light beam normal to the incident beam since the light source and camera are set up at right angles.

The particles chosen for use in this experiment were small, hollow glass spheres called Eccospheres made by Emerson and Cuming. They possess the properties mentioned above. From the photographs of these particles made by Bailey[7] it could be seen that the particles had good velocity measuring as well as flow visualization potential. It was also pointed out by Bailey that the particles were effective because they reflected light from the source on the inner surface of the sphere wall at a calculated minimum angle of 96.4° for water flow. The particles were supplied as a freely flowing powder, ranging in size from 30 to 125 microns in diameter, with a wall thickness of about 2 microns. The diameters of 10 particles chosen at random were measured under a microscope, and an average value of 85 microns was found. The particles were separated according to diameter sizes by use of a series of fine-mesh screens. Screens of mesh size .0035, .0029, and .0017 inches were placed in a stack in the order listed, and a 10-gram sample of particles was added to the top screen. Zero grams were collected in the .0035 inch screen, 1 gram in the .0029 inch screen, 5.8 grams in the .0017 inch screen, 1.7 grams passed through all screens and 1.5 grams were lost as dust. The particles used in this experiment were those collected on the .0017 inch screen. An average particle diameter was found to be .0023 inch by averaging the .0029 inch and .0017 inch mesh sizes since particles within that range were used. From this average diameter the number of particles in a gram was calculated to be 1.92×10^6. The particles contain 95 per cent SiO_2, have a true particle density, or density of the powder, of 0.26 grams per cc, and can withstand temperatures up to 2500 degrees Fahrenheit. Only a small amount of particles is required since about 1 gram was enough to enable flow in the 90 gallon tank to be adequately visualized. The selection of the particles with the range of densities suitable for use in free convective flow of water is discussed in Appendix F. A photograph of a glass sphere magnified 192 times on the original photograph taken using a 35 mm camera is shown in Figure 6.

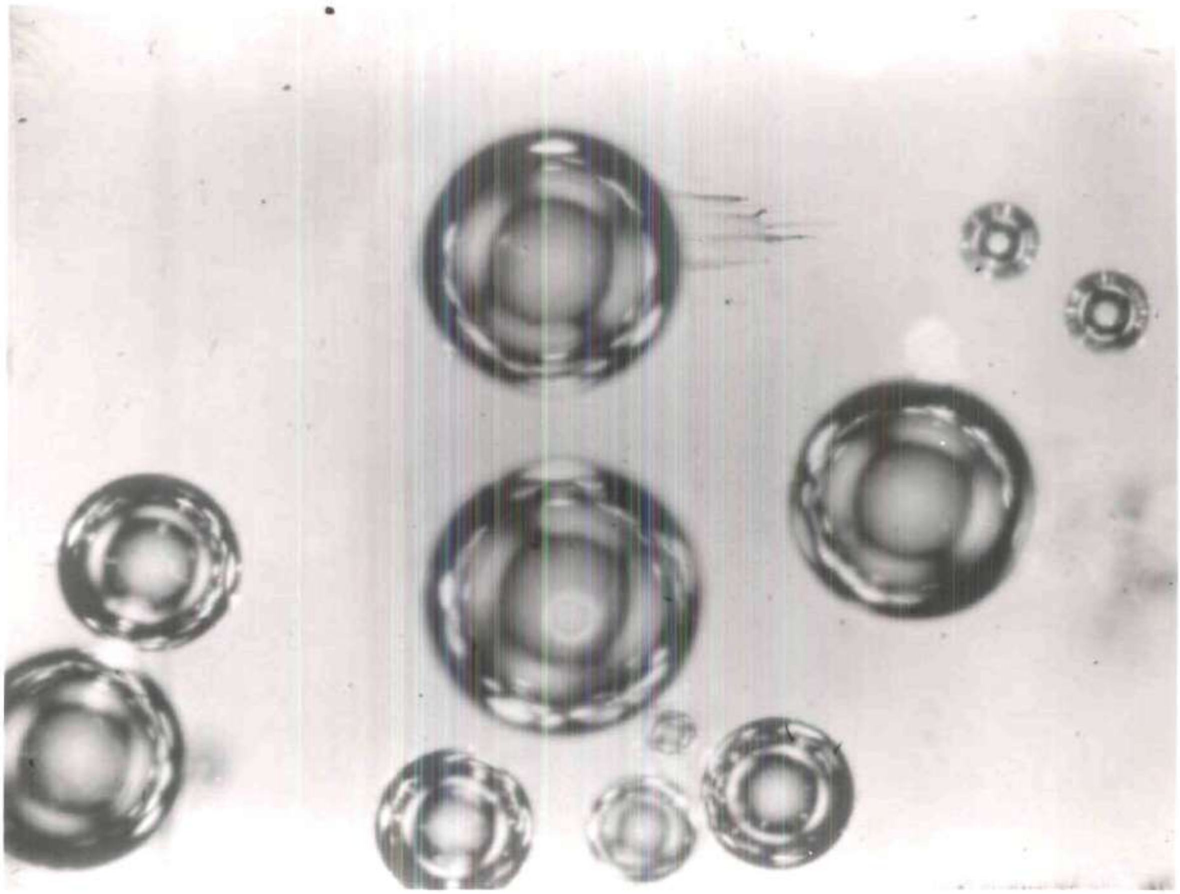

Figure 6. Eccospheres Magnified 192 Times on the Original
35 mm Photograph.

CHAPTER III

PROCEDURE

A technique was established by which photographs of free convective flow in water were successfully taken. The process was developed by trying several methods and choosing the most satisfactory ones.

The first step taken in this experiment was the cleaning and deaerating of the water contained in the tank. It was necessary to remove dust particles, air bubbles, and other impurities from the water so that high contrast photographs could be obtained, and only glass particles would appear in the pictures. Faucet water filling the tank approximately one-third full was filtered using a recirculating filter system for three or four hours until it appeared very clear when a light was shined into it. The tank was then filled to the top with faucet water. It was most effective to filter the water in this manner since most of the impurities could be traced to particles accumulated in the tank and from the air. Also the Atlanta water supply has properties very near those of pure water. Air bubbles which collected on the inside surface of the tank were removed by raking them loose and allowing them to come to the surface of the water.

The position of the camera was established in front of the tank by moving the camera stand and by vertical movement of the camera box. A position was randomly chosen and maintained throughout the entire experiment. The camera was aimed into the center of the tank about seven inches from the bottom. There was a distance of 4 1/2 inches from the lens to the outside surface of the glass and an overall distance of 17 3/16 inches from the front of the lens to the center of the light beam shining into the tank. In order to focus the camera, a wire 10 mil in diameter was lowered into the tank at the center of the light beam. The appropriate adjustments were made on the camera until the wire was seen in sharp focus as viewed on the ground glass at the back of the camera. The lens aperture was set at 4.7, and the shutter was locked open. The camera was then bolted in position.

After the water in the tank was cleaned and the camera focused, the glass microspheres were added to the water. The desired amount of particles was weighed on an analytical balance and then mixed with a little water in a small, flexible, plastic container. A plastic tube 1/4-inch in inner diameter and three feet long was connected to the spout of the container. The tube was placed in the water and submerged by a small weight tied to its tip. As the tip of the tube was moved to different positions within the water, the water-particle mixture was distributed in the tank by a firm, steady squeeze of the container.

After allowing from 5 to 10 minutes for the particles to disperse throughout the tank and for any disturbances caused to die out, the heater plate on the bottom of the tank was turned on. The side heaters were not turned on during the experiment since the pictures were taken at a position near the bottom of the center portion of the tank. Five additional minutes were allowed for convective motion to start in the tank.

One of the four gear-motors was chosen for a particular test and mounted in its position above the camera box. The shutter wheel was then fastened to the shaft of the gear-motor by the set screw provided. One of the four types of films used was placed in the camera and a certain slit size was placed in the light box. The room lights were turned off and the cooling fan for the light box was turned on by flipping the switch located on the light box. Then either all or part of the lamps in the light box were turned on by individual switches also mounted on the camera box. The position of the shutter wheel was checked to be sure that a slit was not in front of the camera lens before exposing the film. The film was then uncovered inside the camera. The switch operating the gear-motor was turned on and the shutter wheel was allowed to make one complete revolution when the 8 and 18 rpm gear-motors were used. This permitted four slits to pass before the camera lens thus exposing the film. A slightly different procedure was used when the 28 and 50 rpm gear-motors were used. The lamps in the light box were turned on after instead of before the shutter wheel was rotated so that the wheel would be turning at full speed before a slit passed in front of the camera lens. Also the wheel was allowed to make more than one revolution since the exposure rate was so fast that the particle trajectories appeared very short on the film. After the film was exposed, the lights were turned off, the shutter wheel was stopped, and the film was again covered. The room lights were turned on, and the film packet or holder was removed from the camera. The Polaroid film was developed, examined, and numbered. The other film was numbered using a device which numbered the film while it was in the film holder. The film was then removed from the holder in the dark and placed in a light-proof box to be developed.

In order to achieve the best photographs possible for velocity measuring purposes from the standpoint of contrast, amount of exposure, trajectory lengths and particle density, different test conditions were employed during the process of taking the pictures. Four different types of film were used. They were, in increasing order of exposure speed, Polaroid Pola Pan 200, Ansco Super Hypan, Kodak Tri-X and Polaroid Pola Pan 3000. The Pola Pan 200 has an ASA equivalent speed of 320. The Kodak Tri-X Pan and Ansco Super Hypan are high speed panchromatic films which combine fine grain with excellent definition. The Polaroid Pola Pan 3000 is an extremely high speed film with an equivalent ASA rating of 3000. These types of film were used so that a wide range of film speed was available. The developer used to develop both the Tri-X and Super Hypan was Kodak H C-110 developer. Different intensities of the light beam were achieved by two types of changes. Either one, two, three, or four lamps in the light box were turned on simultaneously. The size of slit in the end of the light box was either the fully-open, 2-inch slit, the 1/2-inch-wide slit or the 1/4-inch slit. Not only did a decrease in slit size lower the intensity, but it also caused a narrower beam of light which consequently illuminated fewer glass particles in the 0.22-inch depth of field of the camera. The rate of exposure in exposures per second was the number of times a particle trajectory appeared on the film in a second. This rate was controlled to a certain extent by using gear-motors of different speeds to turn the shutter wheel. The gear-motors with rated speeds of 8, 18, 28, and 50 rpm were used for this purpose. The exact number of exposures per second for each gear-motor is given in Appendix D. The density of glass particles in the water was changed from 0.00833 grams per cubic foot of water, or 1.92×10^5 particles per cubic foot, to 5.76×10^5 particles per cubic foot. The purpose of this change was to provide a means of determining the optimum number of particles that would appear in a square inch of a picture from the standpoint of clarity in measuring particle trajectories as well as overall description of the flow. The density of the particles in the water did not remain constant at 1.92×10^5 or 5.76×10^5 particles per cubic foot, which were added initially before a long series of tests were run. In a period of time from 45 to 60 minutes after addition of particles to the water, a noticeable decrease in particle density could be observed. This decrease was due to particles only slightly lighter or heavier than water either rising to the top of the water or falling to the bottom of the tank and remaining there. A discussion of the density variations of the particles is given in Appendix F.

Photographs were taken of the free convective flow such that each photograph was taken under a different combination of the variables mentioned above. Thirty-four pictures for each type of film available were taken. A series of pictures were taken in sequence using the same type film, particle density, and slit but changing the gear-motor and the number of lights. A tabulation of the conditions under which each photograph was taken along with its number is outlined in Table 1.

A process for developing the Tri-X and Super Hypan film was used to increase the contrast of the pictures. A high-contrast lithofilm positive was made of a regular negative. From the lithofilm positive a

Table 1. Photographic Test Conditions

Picture	Film	Particle Density in Particles Per Ft^3	Wheel Speed in rpm	Exposure Rate in Exposures Per Second	Slit Size in Inches
1-4	200	1.92×10^5	7.41	0.494	2
5-8			16.8	1.12	
9-12			28.2	1.88	
13-16			52.1	3.48	
17-20		5.76×10^5	7.41	0.494	
21-24			16.8	1.12	
25-28			28.2	1.88	
29-32			52.1	3.48	
33-36	Hypan	1.92×10^5	7.41	0.494	
37-40			16.8	1.12	
41-44			28.2	1.88	
45-48			52.1	3.48	
49-52		5.76×10^5	7.41	0.494	
53-56			16.8	1.12	
57-60			28.2	1.88	
61-64			52.1	3.48	
65-68	Tri-X	1.92×10^5	7.41	0.494	1/2
69-72			16.8	1.12	
73-76			28.2	1.88	
77-80			52.1	3.48	
81-84		5.76×10^5	7.41	0.494	

(Continued)

Table 1. Photographic Test Conditions (Continued)

Picture	Film	Particle Density in Particles Per Ft^3	Wheel Speed in rpm	Exposure Rate in Exposures Per Second	Slit Size in Inches
85-88			16.8	1.12	
89-92			28.2	1.88	
93-96			52.1	3.48	
97-100	3000	1.92×10^5	7.41	0.494	1/4
100-104			16.8	1.12	
105-108			28.2	1.88	
109-112			52.1	3.48	
113-116		5.76×10^5	7.41	0.494	
117-120			16.8	1.12	
121-124			28.2	1.88	
125-128			52.1	3.48	

The number of lamps burning in the light box was varied from 1-4 for pictures 1-4, etc.

negative print was made and enlarged to a 7 1/2 by 9 1/2 size. The particles appeared on the print as black streaks on a clear background as can be seen in Figure 7.

The Determination of a Free Convective Velocity with a Correction for Distortion

The method by which free convective velocities are determined in demonstrated by a sample calculation with a correction for distortion due to refraction in water. The picture from which the lithofilm sheet shown in Figure 7 was made was taken using Kodak Tri-X film and is numbered Picture 68 in Table 1. Four lamps, the 8 rpm gear-motor, a 1/2-inch slit and a particle density of 1.92×10^5 particles/ft^3 were used during the taking of the picture.

An equation for the true velocity of a particle with a correction for the distortion due to the light traveling in different media has been derived by Tatom[8]. The light in this experiment traveled from the particles through water, glass, and then air to the camera lens. The particle image was thus displaced from its actual position and distorted. The distortion of the image due to the small curvature of the glass was shown to be negligible by Tatom. The true velocity equation as expressed in finite difference form is listed below as equation (1).

$$V_{true} = \left(\frac{R_B - R_A}{\Delta\tau}\right)\left\{\left[1 + \frac{d\delta}{dR_p}\right]^2 + \left[\bar{R}_p - \delta(\bar{R}_p)\right]^2\left(\frac{\theta_B - \theta_A}{R_B - R_A}\right)^2\right\}^{1/2} \qquad (1)$$

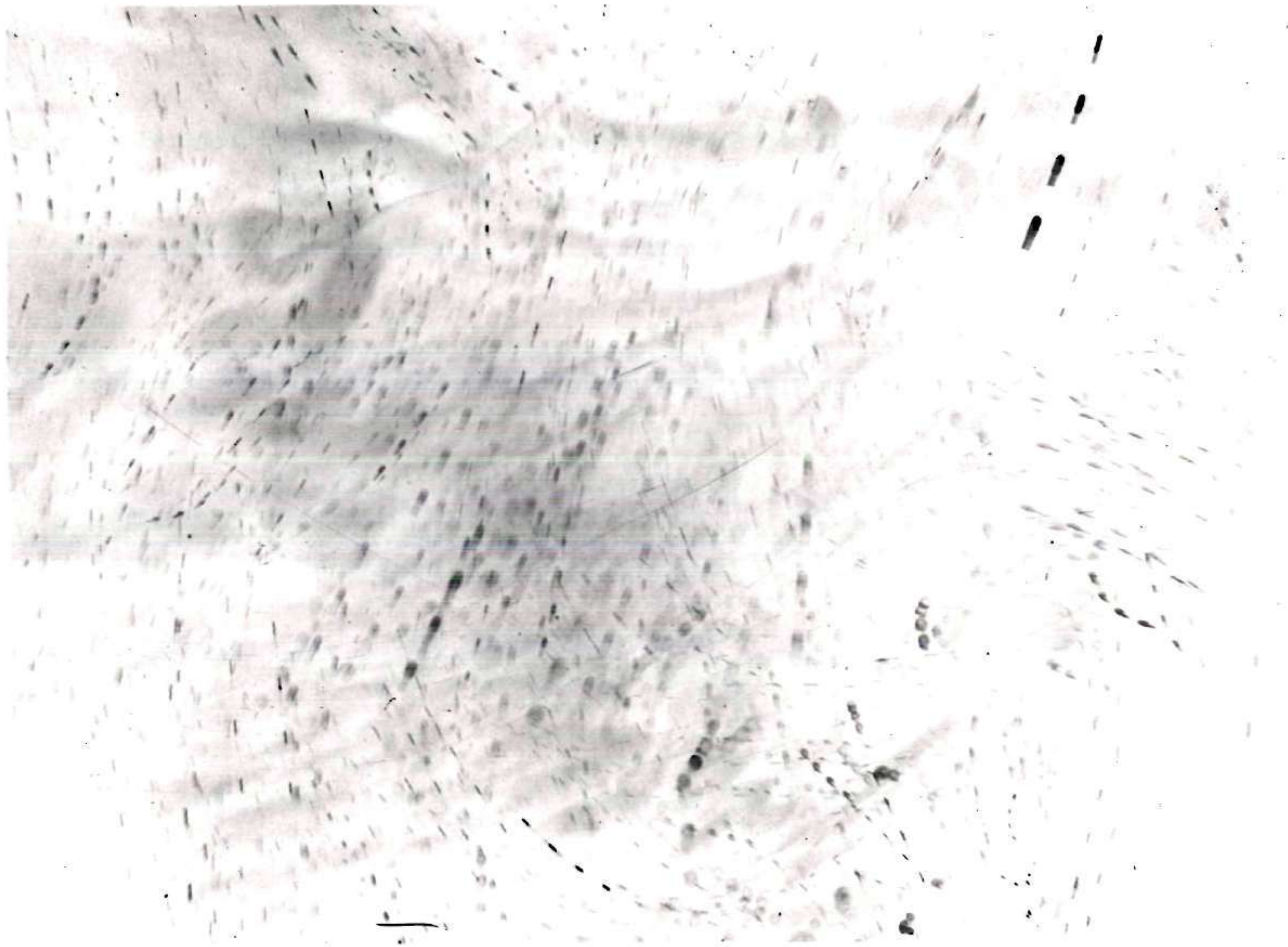

Figure 7. Lithofilm Print.

$$\frac{d\delta}{dR_p} = \frac{t}{\overline{OC}}\left\{1 - \frac{\mu_g^2}{\left[\left(\frac{\bar{R}_p}{\overline{OC}}\right)^2(\mu_g^2-1)+\mu_g^2\right]^{3/2}}\right\} + \frac{D}{\overline{OC}}\left\{1 - \frac{\mu_w^2}{\left[\left(\frac{\bar{R}_p}{\overline{OC}}\right)^2(\mu_w^2-1)+\mu_w^2\right]^{3/2}}\right\} \qquad (2)$$

$$\delta = \frac{\bar{R}_p}{\overline{OC}}\left[(D+t) - \frac{D}{\sqrt{\left(\frac{\bar{R}_p}{\overline{OC}}\right)^2(\mu_w^2-1)+\mu_w^2}} - \frac{t}{\sqrt{\left(\frac{\bar{R}_p}{\overline{OC}}\right)^2(\mu_g^2-1)+\mu_g^2}}\right] \qquad (3)$$

The symbols used in these equations are defined on Page viii.

For convenience in making measurements from the lithofilm, a piece of graph paper was placed over the print. The optical center of the 7 1/2 by 9 1/2 lithofilm was marked on the graph paper. A particle was chosen as an example for determining velocities. The particle appeared on the film as four small trajectories. Two adjacent trajectories were chosen, and the head of the leading one was designated as Point B while the head of the other one was Point A. Lines connecting the points to the optical center of the picture were drawn and labeled R_A and R_B.

In order to determine the scale of the lithofilm print, a picture was made of a measuring device located in the tank at the same position the pictures were taken. From the picture it was determined that the 3 3/4 by 4 3/4 print was 0.51 of the actual size. Since an enlargement of two was used in going from the negatives to the lithofilm prints, a scale factor of 0.98 was multiplied by the distance measurements made in the lithofilm to obtain actual size.

The values used in the calculations are the following:

$$R_A = 2.96 \times 0.98 = 2.90 \text{ inches}$$

$$R_B = 3.12 \times 0.98 = 3.09 \text{ inches}$$

$$\bar{R}_p = \frac{2.90 + 3.09}{2} = 3.00 \text{ inches}$$

$$D = 12.31 \text{ inches}$$

$$O\bar{C} = 17.31 \text{ inches}$$

$$t = 0.375 \text{ inch}$$

$$\mu_g = 1.52$$

$$\mu_w = 1.33$$

The time interval $\Delta\tau$ was determined in the following manner,

gear-motor speed = 7.41 rpm

$$N = 7.41 \frac{\text{rev}}{\text{min}} \times 4 \frac{\text{exp}}{\text{rev}} \times \frac{1 \text{ min}}{60 \text{ sec}} = 0.494 \frac{\text{exp}}{\text{sec}}$$

Since only one exposure length was measured,

$$\Delta\tau = \frac{1}{N} = \frac{1}{0.494} = 2.02 \text{ seconds}$$

Since all the necessary quantities are known, their values are substituted into first equation (3), then equation (2) to obtain values of $\delta = 0.561$ inch, and $\frac{d\delta}{dR_p} = 0.197$. These values were then substituted into equation (1) to obtain a true particle velocity of 0.115 in./sec or 6.9 in./min. The details of the calculations are given in Appendix A. An imaginary particle moving radially from the optical center of the picture with the same trajectory length as the one used in the calculations was found to have a true velocity of 6.77 in./min. An imaginary particle moving so that the end points of its trajectory were the same distance from the optical center of the picture at the same position as the calculated particle, with the same particle length, had a true velocity of 3.58 in./min as calculated from equation (1). It can be concluded that the direction in which the particle is moving relative to the optical center of the picture is an important factor in making corrections of velocities for distortion due to refraction.

For purposes of comparison the velocity of the particle was determined neglecting the effect of distortion. The particle trajectory was measured, multiplied by the scale factor, and divided by the time interval. A velocity of 0.099 in./sec or 5.94 in./min was obtained. This velocity calculated neglecting distortion was 14 per cent slower than the true velocity. This large difference indicates the fact that distortion cannot be neglected in calculating the velocities.

The direction of the particle velocity is away from the optical center of the picture as can be seen from Figure 7 by noting that the brighter part of the trajectory was farther from the optical center.

The pictures taken using the Polaroid 3000 film were not enlarged on the lithofilm prints, although it is possible to do so. These pictures were taken using the 1/4-inch light slit rather than a 1/2-inch or 2-inch slit since the film is a very fast speed film. The narrower slit produces a narrower light beam so the particles cannot move as far in the direction of the line of view during the total exposure time and still be in the light beam. Thus only the particles with a small velocity vector in the line of view will appear during the total exposure time on the photograph. Therefore the two-dimensional measurement of velocity using the 1/4-inch slit is more accurate than that using the 1/2-inch or 2-inch slit.

A photograph is shown in Figure 8 of free convective flow taken using Polaroid 3000 film. Four lamps with the 1/4-inch slit and the 8 rpm wheel were used with a particle density of 1.92 x 10^5 particles/ft^3. Since the method of calculating the velocity is the same as that applied to the previous lithofilm photograph, the values and results, but not the calculations, are presented. The following values were measured for a bright particle near the center of the photograph:

$$R_A = .51 \text{ inch} \times 1.96 = 1.00 \text{ inch}$$

$$R_B = .57 \text{ inch} \times 1.96 = 1.12 \text{ inch}$$

$$\bar{R}_p = 1.06 \text{ inch}$$

$$D = 12.31 \text{ inches}$$

$$\overline{OC} = 17.31 \text{ inches}$$

$$t = 0.375 \text{ inch}$$

$$\mu_g = 1.52$$

$$\mu_w = 1.33$$

$$\Delta\tau = 2.02 \text{ seconds}$$

$$\Delta\theta = 23.5 \text{ degrees} = 0.41 \text{ radians}$$

The following results are found using these values:

$$\delta = 0.199 \text{ inch}$$

$$\frac{d\delta}{dR_p} = 0.196$$

$$V_{true} = 0.186 \text{ in./sec} = 11.1 \text{ in./min}$$

Without the correction for distortion, the velocity is calculated to be .223 in./sec or 13.4 in./min, which differs from the true velocity by

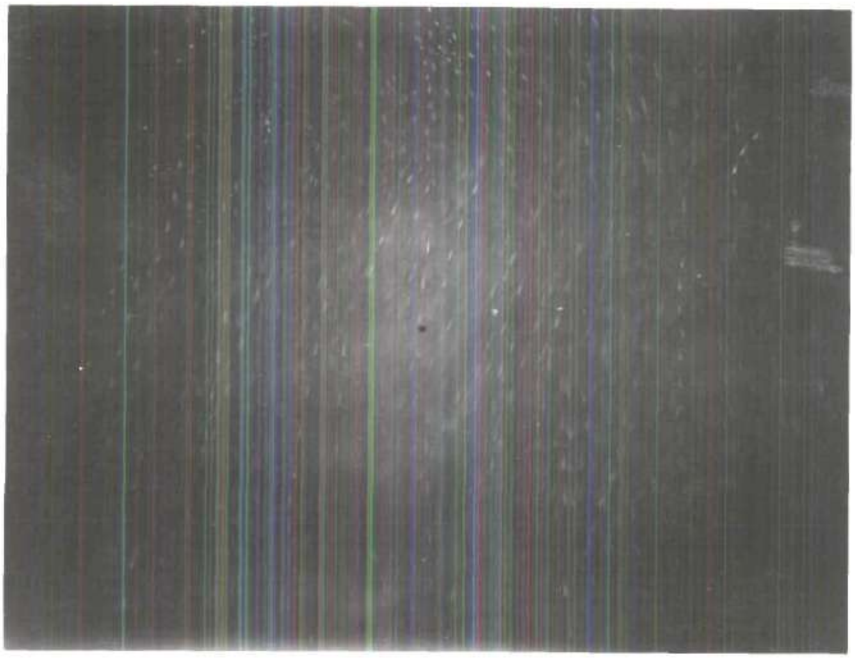

Figure 8. Polaroid 3000, 4 Lamps, 1/4-inch Slit, 1.92×10^5 Particles/ft^3 and 8 rpm Gear-Motor.

20.5 per cent.

Care was taken to choose a particle whose four trajectories were nearly the same size, without some of them being out of focus. The particles shown in the picture with some of the trajectories much larger and dimmer than others were moving out of the depth of field and thus had a substantial velocity in the line of view of the camera.

Application of the Two-Dimensional Technique to Turbulent Flow

For flow in virtually two dimensions, a photograph of an illuminated section gives a good general description of the flow. However, as the degree of turbulence and the motion in the direction along the line of view increases, it becomes increasingly more difficult to analyze the overall motion recorded on the photograph.

Fluids in turbulent flow follow a continually changing motion referred to both time and space. In highly turbulent flow, it is impossible to observe the basic flow pattern from a photograph taken at any one instant since the random motion recovered may appear to have no relation whatever to the basic flow pattern. In less intense turbulence, some relation between the instantaneous tracer motion and the basic pattern can be detected. If several photographs of the turbulent flow are taken at different instances at the same position, the resultant of the velocity vectors found from the different photographs at the same position in the flow would represent the direction and magnitude of the basic flow pattern at that position. By applying this same method to each position in the tank, the entire flow pattern could be determined.

Since the technique of measuring velocities used in this experiment is two-dimensional, the measurement of velocities in the turbulent portion of the tank is that of the average two-dimensional velocities. Symmetry and continuity demands that, on the average, the velocities toward or away from the camera must be zero.

CHAPTER IV

PRESENTATION OF RESULTS

Over one-hundred pictures of free-convective flow were taken to establish a good set of photographic conditions to provide good contrast, an optimum number of particle trajectories per square inch to prevent a cluttered look, a trajectory length convenient for measuring, and an acceptable amount of exposure. A few of the best pictures were chosen to illustrate different conditions under which the pictures were made. These pictures are shown in Figures 9-12.

Picture number 39 shown in Figure 9 was taken on Ansco Super Hypan film. Three lamps with a 2-inch light box slit, a particle density of 1.92×10^5 particles/ft^3 and the 18 rpm gear-motor were used. The contrast of the picture is not as good as in some of the pictures. This is mainly due to the 2-inch slit producing a broad light beam illuminating many particles which were out of focus. It can be seen from the photograph that the exposure rate of about 1/2 exp/sec was slow enough to produce a particle trajectory which can be conveniently measured for particles velocities of the order of 10 in./min. The particles are moving in the direction of the brighter end of the trajectory. In some of the pictures in which the velocities were much lower, the 18 rpm gear-motor produced trajectory lengths so short that it was difficult to measure them as well as to tell which direction they were moving.

In Figure 10 a photograph with a faster exposure rate is shown

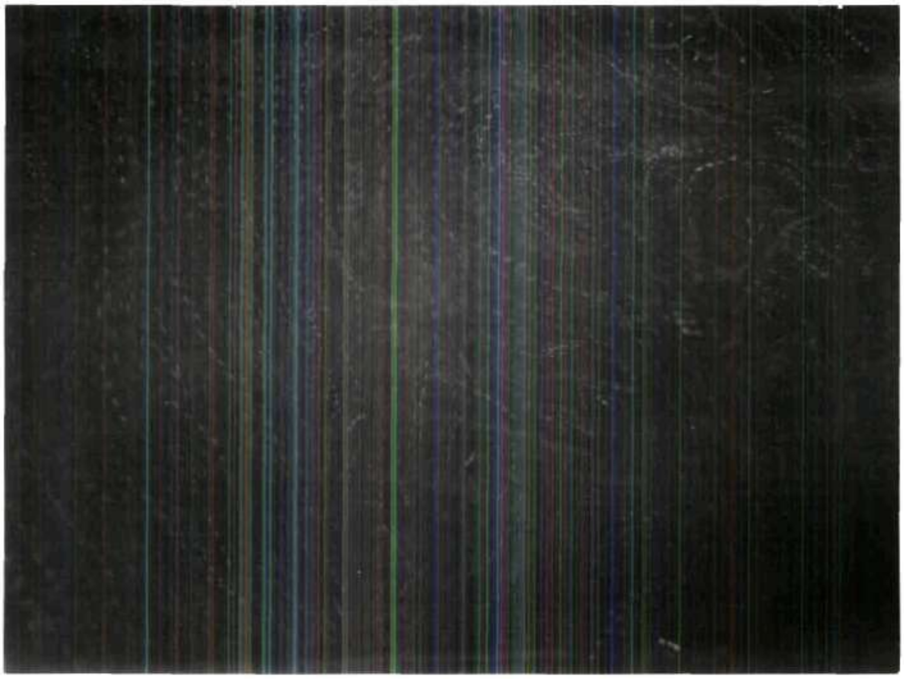

Figure 9. Picture 39 - Super Hypan, 3 Lamps, 2-inch Slit, 1.92×10^5 Particles/ft^3 and 18 rpm Gear-Motor.

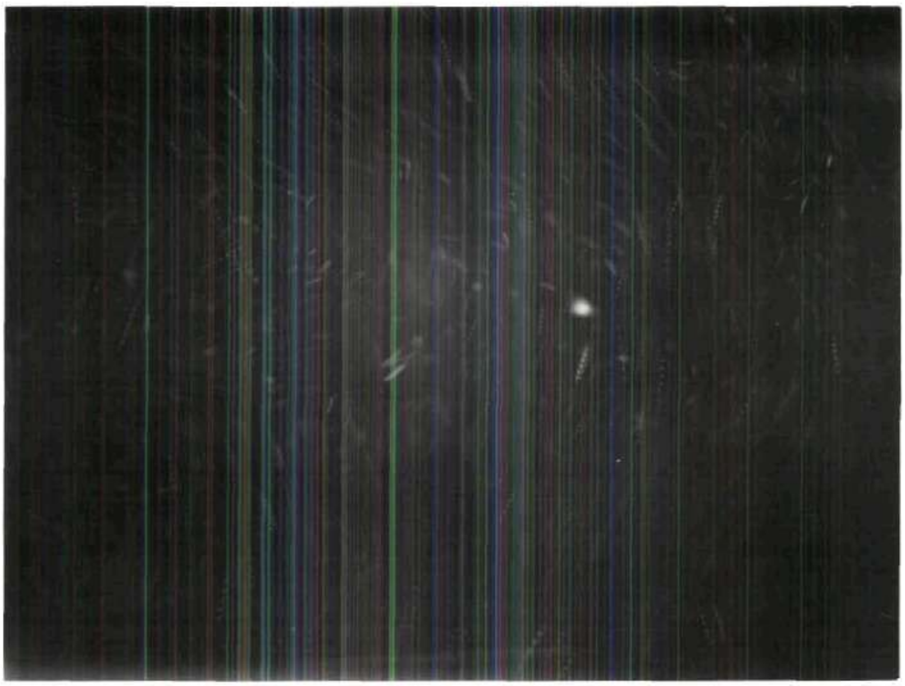

Figure 10. Picture 44 - Super Hypan, 4 Lamps, 2-inch Slit, 1.92×10^5 Particles/ft^3 and 28 rpm Gear-Motor.

using the 28 rpm gear-motor. This picture was taken on Super Hypan film, using 4 lamps, a particle density of 1.92×10^5 particles/ft^3, and the 2-inch slit in the light box. A good contrast was generally obtained by using a fast exposure rate. A disadvantage of using the exposure rate produced by the 28 rpm gear-motor is that for velocities of the order of 10 in./min, the rate was too fast. The particle trajectories were reduced to dots in some cases and it was impossible to distinguish which direction most of the particles were moving. There are no pictures included in which the 50 rpm gear-motor was used. The same comments made about the 28 rpm gear-motor exposure rate also apply to the 50 rpm gear-motor. The fast exposure rate of 3.48 exp/sec produced by the 50 rpm gear-motor would be useful for an application encountering velocities of the order of 4 or 5 ft/min, but was much too fast for use in this experiment.

Pictures number 68 and 83 shown in Figures 11 and 12 were made using Kodak Tri-X film. The 8 rpm gear-motor and the 1/2-inch slit were used for both pictures. Four lamps were used for Picture 68 and three for 83. The main difference that these two pictures illustrate is the density of the particles in the tank. Number 68 was made with a density of 1.92×10^5 particles/ft^3 while 5.76×10^5 particles/ft^3 were used in Number 83. Picture 83 had a cluttered look due to the presence of too many particles whereas all four of the trajectories per particle can be individually followed for almost all of the visible particles in Picture 68. Some particle trajectories are crossing the paths of others in Picture 83, Figure 12. This was due to the fact that the picture was taken at a position in the tank where the flow down and the flow up

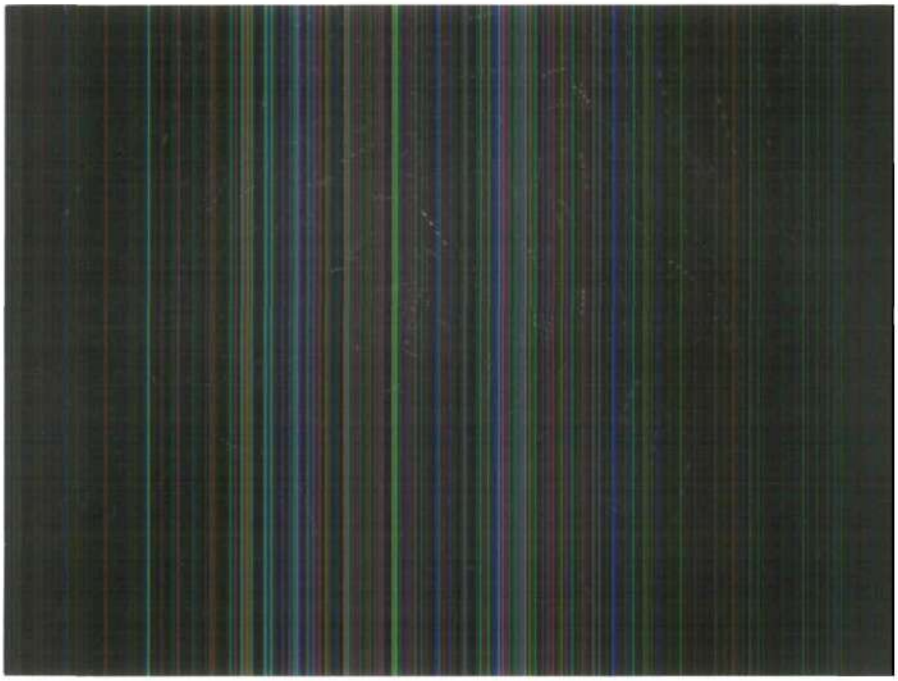

Figure 11. Picture 68 - Tri-X, 4 Lamps, 1/2-inch Slit, 1.92×10^5 Particles/ft^3 and 8 rpm Gear-Motor.

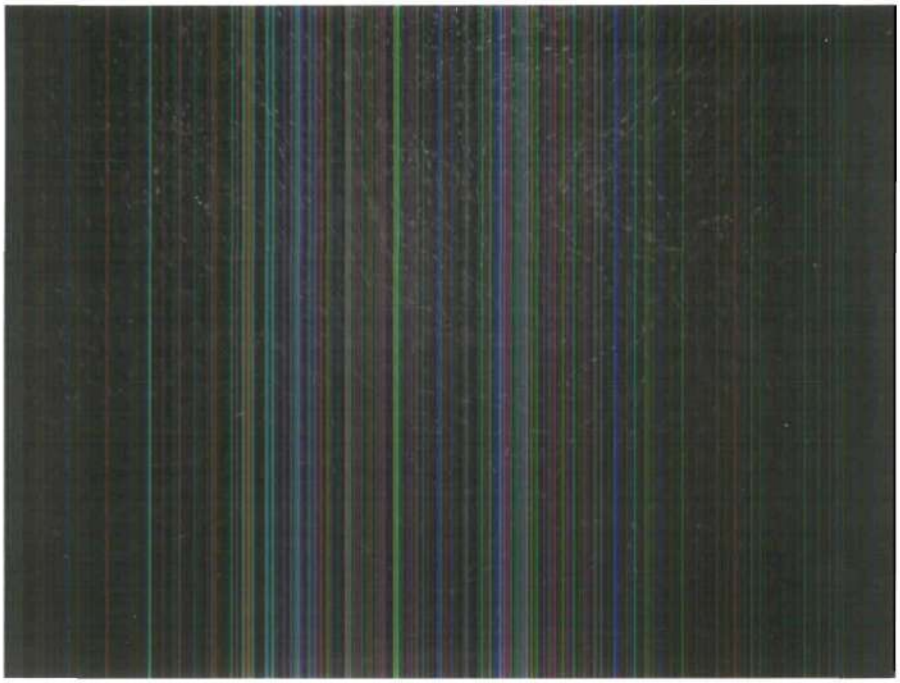

Figure 12. Picture 83 - Tri-X, 3 Lamps, 1/2-inch Slit, 5.76×10^5 Particles/ft^3 and 8 rpm Gear-Motor.

were mixing causing random motion. The random motion and crossing of trajectories is perhaps more noticeable in Figures 9 and 10 than in Figures 11 and 12 since the 2-inch slit illuminates more particles than does the 1/2-inch slit even though the depth of field is 0.22 inch in all cases. Also the eddies would be more evident for the larger slit because they are three-dimensional and the wider slit would permit the particles traveling in a direction with the line of sight a longer time to stay in the picture. The 8 rpm gear-motor was best for use in this experiment since it produced longer particle trajectories which had distinct directional properties. Better contrast was evident in pictures Number 83 and 68 taken with a 1/2-inch slit in the light box than in Pictures 39 and 44 using a 2-inch slit. The narrower slit produced a slimmer beam of light which illuminated fewer particles that were out of the depth of field of the camera.

An attempt was made to use the 1/2-inch slit with the Super Hypan film, but the film was underexposed. Pictures of acceptable quality were obtained using the 2-inch slit with the Super Hypan film. The best pictures were made using the Tri-X film with the 1/2-inch slit since it was possible to use the smaller slit size to provide better contrast. There were no pictures made under exactly the same conditions using Tri-X and Super Hypan film.

Good pictures of the flow were obtained using either two, three, or four lamps. The better pictures were obtained using either three or four lamps. Using the Tri-X film with the 1/2-inch slit and two lamps did not usually provide enough intensity to sufficiently expose the film. Pictures taken using one lamp were underexposed in almost all cases.

Pictures made using Polaroid Pola Pan 200 and 3000 type film were as good as those made using Tri-X and Super Hypan films. Excellent contrast was achieved using the high speed 3000 type film since it was possible to use the 1/4-inch slit in the light box. A disadvantage of the Polaroid film is that no negatives were available for reproductions.

A sample velocity determination for a particle with a correction for distortion due to refraction is given in Appendix A. The velocity was found to be 6.9 in./min. A simple calculation of the velocity made by dividing the trajectory length by the time interval without correcting for distortion for the same particle was made, and the velocity thus calculated of 5.94 in./min differed from the calculation considering distortion by 14.7 per cent. The difference indicated the fact that it is necessary to make a correction for distortion due to refraction of the light beam.

Experimental error was involved in the determination of the velocity. The measurements from the lithofilm were made to the nearest .01 inch. The speed of the gear-motor used in determining the exposure time was measured to the nearest .02 minute. Other distance measurements were made to the nearest 1/32 inch. A detailed discussion of error is given in Appendix C.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

A technique of measuring velocities in free convection was successfully developed by photographing small glass spheres suspended in the water. Changes in light intensity and beam width, exposure rate, particle density, and type of film were made to find the best combination for taking pictures of free convection flow of water in a tank two feet square by three feet tall at a position near the bottom of the tank at the center. From a study of the various pictures, the following conclusions are drawn. Good pictures were obtained using all four types of film available when different size slits in the light box were used for different-speed films. The 1/4-inch slit was used for the 3000 Polaroid, the 1/2-inch slit with the Tri-X film and the 2-inch slit with the Polaroid 200 and the Super Hypan. The narrower the slit size, the better the contrast of the picture since the light beam was narrower and illuminated fewer particles that were out of the depth of field of the camera. The Polaroid film has the advantage of immediate development to give some indication of the quality of the picture so that necessary adjustments could be made. A disadvantage of Polaroid film was the lack of negatives from which prints can be reproduced. Enough light was obtained using either three or four lamps burning together in the light box to expose all film. Little difference in exposure could be denoted between three and four lamps. Two lamps produced sufficient intensity to expose the film in some cases such as for the high speed Polaroid 3000 film and for some of the Polaroid 200 film and Super Hypan in which the 2-inch slit was used along with the larger particle density. One lamp was insufficient for exposure in almost all cases. A particle density of 1.92×10^5 particles/ft^3 was more useful for purposes of velocity measurements than 5.76×10^5 particles/ft^3 although the larger density was better for flow visualization. There were so many particle trajectories per square inch on some of the pictures taken with a density of 5.76×10^5 particles/ft^3 that it was difficult to distinguish one particle from another. The slower exposure rates of .494 and 1.12 exp/sec produced by the 8 and 18 rpm gear-motors turning the shutter wheel produced particle trajectories which could be easily measured and which had a distinct head and tail for purposes of determining directions. The exposure rate and gear-motor that should be used in an application depends on the velocities involved. The 28 and 50 rpm gear-motors produced exposure rates too fast for measuring the velocities in the range of 0 to 15 in./min involved in this experiment. The particle trajectories appeared as dots without any provision for determining the direction in which the particle was moving. Taking all factors into consideration, the best pictures for the purpose of velocity measurements were taken on Tri-X film developed using Kodak HC-110 developer, with a 1/2-inch slit in the light box using all four lamps, a particle density of 1.92×10^5 particles/ft^{3}m with an exposure rate of .494 exp/sec produced by the 8 rpm gear-motor. More accuracy, however, is obtained using the 1/4-inch slit. Picture 68 shown in

Figure 9 is an example of a picture taken under those conditions.

A correction for the velocity must be made for distortion due to refraction. The gear-motors should be run for at least 10 minutes before taking the pictures because there was a light change in speed of the motors during the warm-up period. The small glass spheres should be added to the water a minimum of 15 minutes before taking the picture so that the particles with unacceptable densities would have time to either rise to the top or go to the bottom of the tank.

The process of using high contrast lithofilm enlargements of the pictures was a successful method of removing most of the undesirable particles which were out of focus on the negative and simplified the process of measuring particle trajectories used in the determination of the velocities.

Recommendations

The conditions which produced the best pictures of the flow in this experiment would not necessarily be the same for other applications.

If a tank 10 feet tall with the same cross-section as the 3-foot tank used in this experiment were used the intensity at the bottom of the 10-foot tank would be much less than the intensity was at the position at which the pictures were taken in this experiment. In order to obtain an acceptable picture, it might be necessary to use the Tri-X film developed with a fast developer with the 2-inch slit and a particle density of 1.92×10^5 particles/ft^3 rather than the 1/2-inch slit and 5.76×10^5 particles/ft^3. Good contrast would be sacrificed for the sake of obtaining enough light for exposure. If the Tri-X film was not fast enough, the high speed Polaroid film could be used with a wide slit opening. If no film available was fast enough, the intensity of light produced by the lamps in the light box could be greatly increased by increasing the input voltage to the lamps.

No problems should be encountered in taking pictures near the top of the tank. Over-exposure of the film could be easily corrected by decreasing the lens aperture of the camera.

The four gear-motors of 8, 18, 28, and 50 rpm should provide exposure rates acceptable for measuring velocities in the approximate range of 0 to 50 in./min.

The semicircular tube described in Appendix E could have been made with a circular cross-section instead. A comparison using the approximate velocity profile in a pipe could have been made by measuring particle trajectories in the center of a circular tube where the distortion due to curvature would be minimum.

The velocity measuring technique used in this experiment would be a useful method for measuring velocity profiles in containers having cross-sections of various geometry. The velocities of particles moving at different positions in semicircular tube and at different distances from the water surface were found to vary in such a manner that a velocity profile could be determined.

Several improvements could be made in the apparatus used in this experiment to give more accurate results. The lenses placed in front of the lamps in the light box were of such a poor quality that they didn't completely collimate the light beam. A narrower light source than the 1/2-inch diameter lamps would also give a narrower beam. A narrower slit in the end of the light box would have produced a narrower light beam. Slits in series in the light box would have aided in collimating the beam as well as producing a narrower beam. The object in providing a very narrow beam is to illuminate particles which are moving in two dimensions only so that the particles with a substantial component of velocity in the direction of the line of view of the camera will appear for only a very short interval of time in the light beam. A smaller depth of field would be obtained if the camera could be moved closer to the plane of observation. A smaller depth of field would also help to identify particles moving with an appreciable velocity in the line of view, such as turbulent eddies. If the depth of field was extremely small, of the order of 1/1000 of an inch, and was accurately known, then all particles that had moved out of the small region defined by the depth of field could be determined by specifying a measurable increase in the size of the particle image on the photographic plate. A depth of field that small could be obtained only by focusing on an object close to the camera and providing a special lens arrangement.

APPENDICES

APPENDIX A

DETAILED CALCULATIONS OF A FREE CONVECTIVE VELOCITY WITH A CORRECTION FOR DISTORTION

The details of the sample calculation of a free convective velocity with a correction for distortion as outlined in Chapter III are given below. Since the methods by which the quantities were obtained have been previously discussed, only the values used and the equations are given.

Using the equations derived by Tatom[8] for the true particle velocity correcting for distortion due to refraction, it was first necessary to calculate the distance δ between the apparent and true particle position from equation 3. From the sample given in Chapter III the following values are used:

$R_A = 2.90$ inches

$R_B = 3.09$ inches

$\bar{R}_p = 3.00$ inches

$D = 12.31$ inches

$\overline{OC} = 17.31$ inches

$t = 0.375$ inches

$\Delta\tau = 2.02$ inches

$\mu_w = 1.33$

$\mu_g = 1.52$

$\Delta\theta$ = .035 radians

Substituting into equation 3,

$$\delta = \frac{\bar{R}_p}{\overline{OC}}\left[(D+t) - \frac{D}{\sqrt{\left(\frac{\bar{R}_p}{\overline{OC}}\right)^2(\mu_w^2-1)+\mu_w^2}} - \frac{t}{\sqrt{\left(\frac{\bar{R}_p}{\overline{OC}}\right)^2(\mu_g^2-1)+\mu_g^2}}\right] \tag{3}$$

$$\delta = \frac{3.00}{17.31}\left[(12.31+0.375) - \frac{12.31}{\sqrt{\left(\frac{3.00}{17.31}\right)^2(1.33^2-1)+1.33^2}} - \frac{0.375}{\sqrt{\left(\frac{3.00}{17.31}\right)^2(1.52^2-1)+1.52^2}} \tag{3a}$$

$$\delta = 0.173\,[12.69 - 9.20 - 0.245] = 0.561 \text{ inches} \tag{3b}$$

Then using equation 2 to calculate the rate of change of distortion with radius $\frac{d\delta}{dR_p}$,

$$\frac{d\delta}{dR_p} = \frac{t}{\overline{OC}}\left\{1 - \frac{\mu_g^2}{\left[\left(\frac{\bar{R}_p}{\overline{OC}}\right)^2(\mu_g^2-1)+\mu_g^2\right]^{3/2}}\right\} + \frac{D}{\overline{OC}}\left\{1 - \frac{\mu_w^2}{\left[\left(\frac{\bar{R}_p}{\overline{OC}}\right)^2(\mu_w^2-1)+\mu_w^2\right]^{3/2}}\right. \tag{2}$$

$$\frac{d\delta}{dR_p} = \frac{0.375}{17.31}\left\{1 - \frac{(1.52)^2}{\left[\left(\frac{3.00}{17.31}\right)^2(1.52-1)+1.52^2\right]^{3/2}}\right\} + \frac{12.31}{17.31}\left\{1 - \frac{1.33^2}{\left[\left(\frac{3.00}{17.31}\right)^2(1.33^2-1)+1.33^2\right]^{3/2}}\right\} \tag{2a}$$

$$\frac{d\delta}{dR_p} = \frac{0.375}{17.31}\{1-0.64\} + \frac{12.31}{17.31}\{1-0.735\} = 0.197 \tag{2b}$$

Applying equation 1 using the previously calculated results, the true velocity is found,

$$V_{true} = \left(\frac{R_B - R_A}{\Delta\tau}\right)\left\{\left[1 + \frac{d\delta}{dR_p}\right]^2 + \left[\bar{R}_p - \delta(\bar{R}_p)\right]^2 \left(\frac{\theta_B - \theta_A}{R_B - R_A}\right)^2\right\}^{1/2} \tag{1}$$

$$V_{true} = \left(\frac{3.09 - 2.90}{2.02}\right)\left\{\left[1 + 0.197\right]^2 + \left[3.00 - 0.561(3.00)\right]^2 \left(\frac{.820 - .785}{3.09 - 2.90}\right)^2\right\}^{1/2} \tag{1a}$$

$$V_{true} = 0.0942\left\{1.435 + 0.0585\right\}^{1/2} = 0.115 \text{ in./sec} = 6.90 \text{ in./min} \tag{1b}$$

If the distortion error due to refraction is neglected, the velocity can be simply calculated by measuring the trajectory length, multiplying it by the scale factor and dividing by the time interval.

Trajectory length (L) = 0.20 inches

Scale factor (S) = 0.98

Time interval ($\Delta\tau$) = 2.02 seconds

$$V = \frac{LS}{\Delta\tau} = \frac{0.20 \times 0.98}{2.02} = 0.098 \text{ in./sec} = 5.86 \text{ in./min}$$

The per cent difference between the true velocity and the velocity neglecting distortion was calculated in the following manner:

$$\text{Per Cent difference} = \frac{0.115 - 0.098}{0.115} \times 100 = \frac{.017}{0.115} \times 100 = 14.7\%$$

APPENDIX B

CALCULATION OF DEPTH OF FIELD

The depth of field of the optical system is an important parameter in this experiment. It is defined as the distance between the points nearest to and farthest from the camera that appears in sharp focus. All the particles in the region determined by the depth of field would be in sharp focus until they moved out of the depth of field.

In order to calculate the depth of field, it is first necessary to find the apparent image position since the light travels through different media.

Figure 13 shows a light beam traveling from a point in the focal plane on the center line of the view to the outer extreme of the lens of the camera, point P, with the vertical scale greatly exaggerated. Using trigonometric relationships and Snell's laws, the following equations can be written:

$$\tan \Phi_3 = \frac{a}{12} \qquad (1)$$

$$\tan \Phi_2 = \frac{b}{3/8} \qquad (2)$$

$$\tan \Phi_1 = \frac{c}{5} \qquad (3)$$

$$a + b + c = 0.47 \qquad (4)$$

$$\sin \Phi_1 = 1.52 \sin \Phi_2 \qquad (5)$$

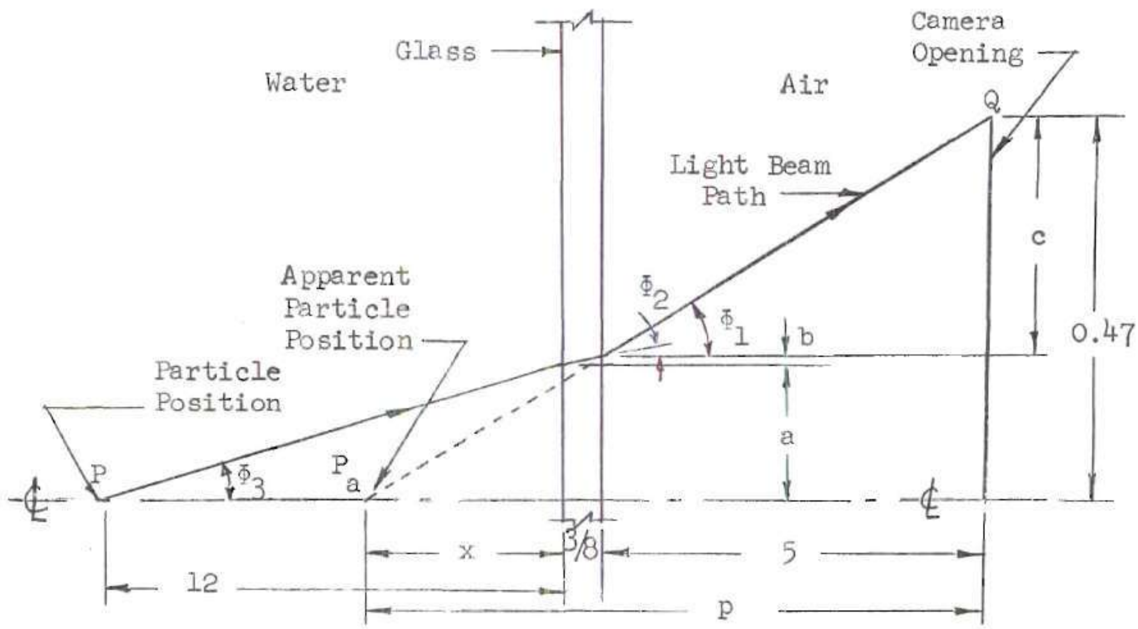

Figure 13. Apparent Image Position

$$1.52 \sin \Phi_2 = 1.33 \sin \Phi_3 \tag{6}$$

$$x + \frac{3}{8} = \frac{a + b}{\tan \Phi_1} \tag{7}$$

Solving these equations together and using the approximation that the tangent of small angles equals the sine, the following values are obtained:

$$\Phi_1 = 1.89°$$

$$\Phi_2 = 1.24°$$

$$\Phi_3 = 1.43°$$

$a = 0.297$ inch

$b = 0.0081$ inch

$c = 0.165$ inch

$x = 8.93$ inches

The distance of the apparent image from the center of the lens is $p = 13.3$ inches.

The following mathematical expression for the depth of field is derived by Hardy and Perrin[10]:

$$d = \frac{z'p}{m\rho - z'} + \frac{z'p}{m\rho + z'} \qquad (8)$$

where z' is the radius of the circle of confusion, p is the distance from the apparent object to the center of the lens, m is the magnification of the object, and ρ is the radius of the camera entrance pupil. A rather common value for z' for precise photographic work is 0.05 mm or .002 inch. The object distance was 13.3 inches, the magnification was determined to be 0.51, and the radius of the camera opening was calculated to be 0.47 by dividing the f/setting of 4.7 by the 5-inch focal length of the camera thus obtaining the diameter of the opening. The above values are substituted into equation 8:

$$d = \frac{(.002)(13.3)}{(.51)(.47) - .002} + \frac{(.002)(13.3)}{(.51)(.47) + .002}$$

$$d = \frac{(.002)(13.3)}{.238} + \frac{(.002)(13.3)}{.242}$$

$$d = .112 + .110$$

$$d = .222 \text{ inch}$$

The smallest depth of field possible was desirable in this experiment. Particles moving with a velocity component in the line of view of the camera would become large and out of focus when they moved out of the depth of field of the optical system. The smaller the depth of field, the shorter the distance the particles could move before becoming out of focus. Thus the particles moving with a substantial velocity in the line of view could be distinguished from those moving in essentially two-dimensional flow since the former would have some trajectories large and out of focus. Velocity measurements made with a small depth of field are more accurate than those made with a larger depth of field since particles having essentially two-dimensional flow can be distinguished from the others and measured with the two-dimensional technique.

The depth of field of 0.22 inch used in this experiment is amaller than the width of the minimum light beam used in this experiment. Thus particles moving out of the depth of field of the optical system are still illuminated and appear out of focus, as can be seen in Figure 8.

APPENDIX C

DISCUSSION OF ERRORS

There is an error involved in making local velocity measurements of turbulent flow using the two-dimensional technique employed in this experiment due to the three-dimensional eddies. The velocity vector in the line of view cannot be measured. The velocity that is measured is the velocity vector perpendicular to the line of view. There was evidence from the photographs of three-dimensional flow. There were fewer particle traces for some of the particles than for others, indicating the fact that some particles moved out of the depth of field and the light beam during the total exposure time of the photograph. The width of the light beam at the position where the pictures were taken was approximately 0.38 inch and the depth of field of the optical system was about 0.22 inch. For velocities of 6 in./sec, close to the free convective velocities measured, a depth of field of 0.22 inch, and a total exposure time of about 10 seconds, the maximum error in velocity measurement due to neglecting the third velocity component is approximately 2.3 per cent as calculated in the manner shown below:

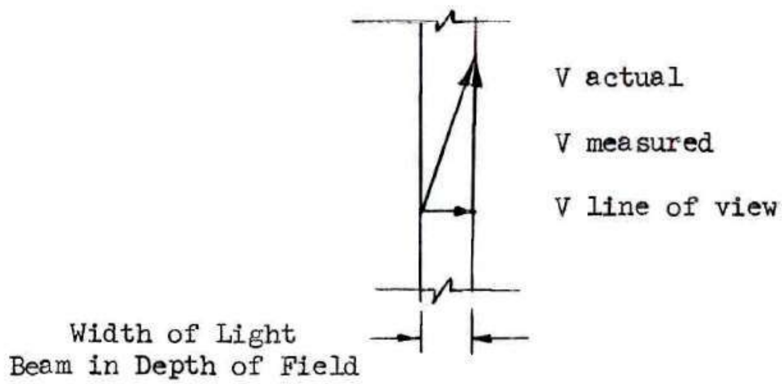

Figure 14. Velocity Components.

$$V \text{ measured} = \sqrt{V^2 \text{ actual} - V^2 \text{ line of view}}$$

$$= \sqrt{6^2 - 1.32^2}$$

$$= \sqrt{34.26} \quad = 5.86$$

$$\text{Per cent error} = \frac{6 - 5.86}{6} \times 100 = 2.3 \text{ per cent}$$

A narrower light beam or a smaller depth of field would have limited the distance the particle could travel in the line of view of the camera and still be illuminated and in focus. The smaller that distance is the smaller will be the allowable component of velocity in the line of view thus giving a more accurate velocity measurement. The velocity vector in the line of view of the camera could possibly have been determined by a technique not employed in this experiment. If a long exposure time of 15 or 20 seconds had been used allowing a large number of trajectories rather than the usual four, the particles moving with an appreciable velocity in the line of view would have traversed the depth of field and would not have appeared on the photograph the total exposure time. The trajectories on both ends of the particle path would appear large and out of focus. Knowledge of the number of trajectories in focus and the exposure time per trajectory would have permitted the calculation of the velocity in the line of view of the camera. The above discussion pertains to local velocity measurements. The technique applicable to determining the overall average flow field in turbulent flow is discussed in Chapter III.

Some error can be expected in making the measurements of trajectory lengths from the photographs. It was possible to read the scale used in taking the measurements to the nearest .01 inch. A more accurate measuring device would help reduce the error in measuring the velocities.

There was also some error involved in determining the speed of the shutter wheel, which determined the exposure time. The stop watch used to time the rotation could be read to the nearest .01 minute.

Very little error in the velocity determination can be traced to the failure of the particles to accurately follow the motion of the fluid. If sufficient time is allowed, as explained in Appendix F, for the particles much lighter or heavier than water to separate from the water, the remaining particles have the same density as that of the water in which they are suspended.

APPENDIX D

GEAR-MOTOR CALIBRATION

An accurate determination of speed and how constantly the gear-motors turned the shutter wheel was necessary for determining the exposure time used in calculating velocities. An experiment was set up to show what effect a change in input voltage would have on the speed of the gear-motors. A gear-motor disconnected from the shutter wheel was electrically connected to a Powerstat made by Superior Electric Company. The output voltage of the powerstat could be varied from 0 to 140 volts, and the maximum power output was 1 KVA. In the experiment the voltage was varied from 115 to 75 volts. The speed at which the shaft of the gear-motor was turning was measured by counting a certain number of revolutions that the shaft turned and timing the number of revolutions with a stop watch. The results of this experiment are tabulated in Table 2. It can be seen from the results that a large change in voltage produced only a small change in speed. A change in voltage from 115 to 110 volts caused a change in speed of less than 1/2 per cent for each gear-motor. It can be concluded that any minor change in voltage that might occur during the operation of the gear motors would produce an insignificant change in motor speed.

The speed of a gear-motor with the shutter wheel attached was measured by timing a certain number of revolutions of the shutter wheel again using a stop watch. Continual trial timings were made over a short period of time from 5 to 10 minutes until the same speed was recorded for at least four consecutive trials, which indicated that a constant speed of rotation had been reached. The results of the trial timings are recorded in Table 3. These results indicate that during a short warm-up period of the gear-motors there is a small increase in speed, but after the warm-up period they tend to perform at a constant speed. The per cent variation in speed for the 18 rpm gear-motor was approximately 2.5 per cent, 1.5 per cent for the 8 rpm motor and less than 1.0 per cent for the 28 and 50 rpm gear-motors. The speeds used in calculating velocities in this study were the speeds recorded in the first trial timing for each gear-motor since no warm-up time was allowed during the taking of the pictures.

Table 2. Change of Gear-Motor Speed with Voltages

Gear-Motor	Voltage in Volts	Revolutions Counted	Time in Seconds	Speed in rpm
8 rpm	75	8	64.0	7.50
	80		63.4	7.57
	85		63.4	7.57
	90		63.0	7.62
	95		63.0	7.62
	100		62.9	7.63
	105		62.8	7.64
	110		62.8	7.64
	115		62.7	7.65
18 rpm	75	18	62.7	17.2
	80		61.2	17.6
	85		60.9	17.7
	90		60.0	18.0
	95		60.0	18.0
	100		60.0	18.0
	105		59.4	18.2
	110		59.1	18.3
	115		58.8	18.4
28 rpm	75	25	53.6	28.0
	80		52.8	28.4
	85		52.4	28.6
	90		51.8	29.0
	95		51.8	29.0
	100		51.6	29.1
	105		51.6	29.1
	110		51.5	29.1
	115		51.4	29.2
50 rpm	75	50	56.8	52.8
	80		56.6	53.0
	85		56.2	53.4
	90		56.2	53.4
	95		56.2	53.4
	100		56.1	53.5
	105		56.1	53.5
	110		56.1	53.5
	115		56.0	53.6

Table 3. Determination of Speed Variation of Gear-Motors During Warmup Period

Trial	Gear-Motor	Revolutions Counted	Time in Minutes	Speed in rpm
1	8 rpm	8	1.08	7.41
2			1.07	7.48
3			1.07	7.48
4			1.06	7.52
5			1.06	7.52
6			1.06	7.52
7			1.06	7.52
1	18 rpm	18	1.07	16.8
2			1.06	17.0
3			1.05	17.1
4			1.04	17.3
5			1.04	17.3
6			1.04	17.3
7			1.04	17.3
1	28 rpm	25	0.890	28.2
2			0.885	28.3
3			0.885	28.3
4			0.885	28.3
5			0.885	28.3
1	50 rpm	50	0.96	52.1
2			0.95	52.6
3			0.95	52.6
4			0.95	52.6
5			0.95	52.6

APPENDIX E

USE OF THE PHOTOGRAPHIC TECHNIQUE FOR MEASURING VELOCITIES OF WATER DRAINING FROM A TUBE

The photographic technique applied to free convective velocities was used to measure velocities at which water drained from a semicircular tube. The tube was initially intended to provide a known velocity which could be used for a comparison of the photographic technique used in this thesis. However, it was discovered that the velocity profile formed in such a manner that even at a short distance of one inch from the water surface the velocities of the water near the center of the tube were about 10 per cent greater than the average velocity at which the tube drained. Due to the uncommon shape of the tube, no solution for the velocity profile could be found for a comparison. The tube was made with a semicircular rather than a square cross-section due to ease of construction and availability of material. The tube shown in Figure 15 was made of 1/8-inch plexiglas 54 inches tall having an inner diameter of 5 3/4 inches with a spot light shining through a 1/8-inch slit into the tube. The tube was made with a flat side so that velocity errors caused by distortion due to curvature would be minimized. The average velocity at which the tube drained was determined by weighing the water that drained from it for a certain time interval and also by photographing the water surface as it moved down the tube. Water filling the tube to the top was drained through a 3/8-inch hole in the bottom to which was connected a valve. Glass spheres placed in the water were photo-

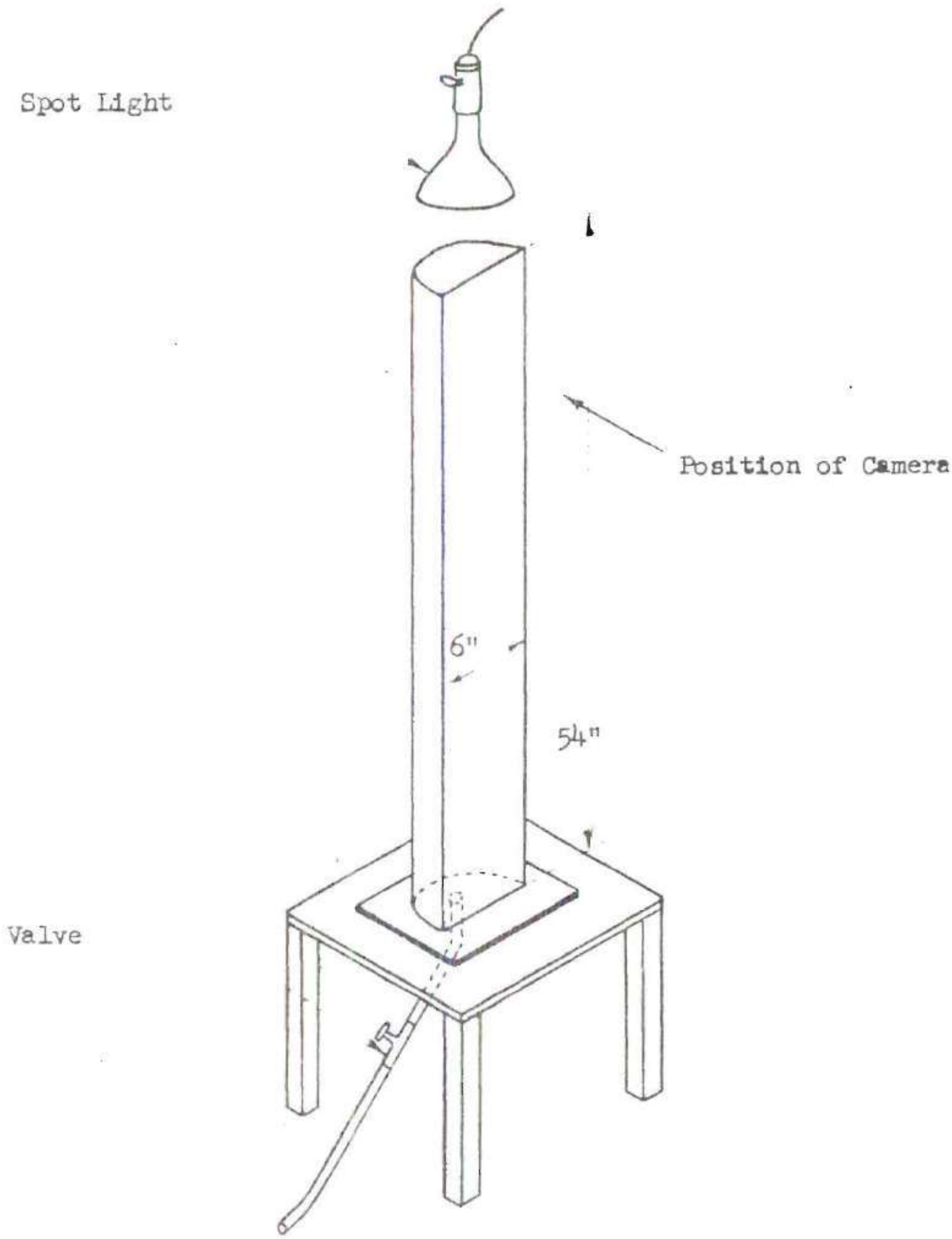

Figure 15. Semicircular Tube.

graphed as they moved with the draining water using the camera-shutter system with the camera looking into the plane side of the tube near the top. The curved, inside surface of the tube was painted flat black to prevent undesirable reflections.

The water used to fill the tube was deaerated before the glass particles were added. The camera was positioned in the camera box so that the pictures were taken in a region from 7/8 to 4 3/8-inches from the top of the tube and 1 1/8-inches from the inside surface of the flat side. After the particles were added to the water, a period of approximately 30 minutes elapsed before a picture was taken. This length of time was used so that most of the motion in the tube would be damped out, and the particles would be suspended motionless in the water. The 18 rpm gear-motor used to turn the shutter wheel was started 10 minutes before the picture was taken so that it would reach equilibrium operating conditions and a constant speed of rotation. The type of film used to take the pictures was Polaroid 200 and the lens aperture of the camera was set at f4.7. The 150-watt spot light was placed above the top of the tube at a distance of 6 inches, and the top of the tube was covered except for 1/8-inch slit. After the room was darkened, the valve at the bottom of the tube was opened allowing the tube to drain. The spot light was turned on until the desired number of slits had passed in front of the camera lens exposing the film and was then turned off. Several pictures were made using this procedure.

The average velocity at which the tube drained during the taking of a picture was determined first by a weighing process. The water that drained from the tube over time intervals of .10, .15, and .20

minutes as measured by a stop watch was collected in a container and weighed to the nearest tenth of a gram on a pair of scales. The weights are tabulated in Table 4. By knowing the cross-sectional area of the tube, an average velocity was calculated to be 10.04 ± 0.11 in./min for a 95 per cent confidence limit. The average velocity at which the tube drained decreased as the head of water decreased. However, since the head of water decreased less than one inch during the taking of a picture and the tube was 54 inches tall, the average velocity decreased less than 1 per cent and was thus considered constant.

The other method used to determine the average velocity at which the tube drained was the photographing of the water surface as it moved down the tube. Due to continuity the moving water surface is one-dimensional flow. Using the procedure previously described, a picture was taken of the moving surface, and the velocity was determined from knowledge of the exposure rate, scale factor, and distance moved. An average velocity of 10.11 in./min determined in this manner was greater than the velocity of 10.04 in./min as found from a weighing process by 0.65 per cent.

The velocities at which the water was moving at various positions within the tube near the water surface was determined by photographing glass particles. Several pictures were taken of the particles using the procedure previously described. The trajectories of 12 randomly chosen particles were measured to the nearest .01 inch and the exposure rate was determined to be 69.5 exp/min. In Table 5 is given the position of the particle, the trajectory length, and the particle velocity as determined from the exposure rate and trajectory length. The distance from

Table 4. Weights Used in Determining Average Velocity at which the Tube Drained.

Trial	Time in Minutes x 10^2	Weight in Grams	Velocity in Inches Per Minute
1	10	237.0	10.06
2		227.6	9.64
3		230.0	9.76
4		236.6	10.04
5		228.4	9.67
6		238.4	10.12
7		234.6	9.95
8		237.5	10.09
9		240.7	10.22
10		231.0	9.78
11		241.5	10.28
12		227.0	9.60
13	15	358.5	10.39
14		330.5	9.55
15		370.0	10.72
16		354.2	10.26
17		353.0	10.21
18		353.3	10.22
19	20	458.0	10.08
20		450.3	9.87
21		459.2	10.09
22		465.0	10.20
23		457.2	10.04
24		458.3	10.04

Table 5. Velocities at Various Positions Near the Water Surface of the Draining Tube Determined by Photographing Glass Particles.

Distance from Water Surface in Inches	Distance from Inside Wall of Tube in Inches	Length of Particle Trajectories in Inches	Velocity in Inches per Minute
0.54	1.38	0.83	10.48
0.86	1.28	0.83	10.48
0.91	2.58	0.87	10.99
0.99	2.32	0.86	10.90
1.04	2.60	0.85	10.89
1.14	1.23	0.83	10.48
1.15	2.68	0.85	10.89
1.40	1.32	0.92	11.62
1.59	1.36	0.88	11.10
1.76	1.88	0.87	10.99
2.09	1.50	0.94	11.85
2.19	2.28	0.98	12.37
1.30 (Average)	1.87	0.88	11.09

the inner surface of the tube as tabulated in Table 5 is the distance from the position of the particle to the inside surface of the tube as measured on line with the plane of the picture which was taken in all cases at a distance of 1 1/8-inches from the flat side of the tube. The conclusions that can be drawn are that at a larger distance from the water surface at the same distance from the tube wall velocities are greater, while at the same distance from the water surface the velocities are smaller nearer the wall. This is due to a velocity profile formed in the tube. If the velocities of enough different particles were determined, the velocity profile could be established. The average velocity of 11.09 in./min determined by photographing the particles was 9.7 per cent greater than the average velocity of 10.11 in./min at which the tube drained as determined by photographing the moving water surface. This difference was due to the fact that the particles whose velocities were measured were near the center of the tube and had velocities larger than the average because of the velocity profile in the tube.

Table 6. Average Velocities at Which Tube Drained Determined by Three Methods.

Velocity Determined by Weighing in Inches per Minute	Velocity Determined by Photographing Water Surface in Inches per Minute	Velocity Determined by Photographing Glass Particles in Inches per Minute
10.04	10.11	11.09

APPENDIX F

DENSITY VARIATIONS OF THE GLASS SPHERES

An experiment was devised so that the small velocities of the glass particles due to density differences between the water and the particles could be estimated over certain periods of time after adding the particles to the water. A graduated cylinder was filled with water, and the particles were added as uniformly as possible without causing excessive motion of the water in the cylinder. Immediately after adding the particles to the water, many of the particles were seen rising rapidly to the top of the water level while a few were seen descending to the bottom of the cylinder. If the assumptions are made that the motion in the cylinder caused by disturbing the water would stop in approximately 15 minutes and there are no convective forces present, the average velocity by which the particles moved after a time interval was estimated by timing with a stop watch the movement of 20 particles chosen at random. The average was influenced by many particles which appeared to have not motion at all. The crude estimates of average velocities of the particles due to density differences were found for time intervals of 15, 20, 25 and 30 minutes after addition of particles to be .14, .11, .09 and .08 inch per minute respectively. The results of this experiment indicate that slightly better accuracy can be obtained in measuring velocities if a longer time interval is used. Even for a 15 minute time interval, the error in measuring velocities of the order of 1/2-foot per minute would be only about 2 per cent.

APPENDIX G

LIGHT INTENSITY OF THE LIGHT BOX

The intensity of the light beam produced by the light box was measured using a Gossen Lunasix cadmium sulfide type light meter. The intensity of the light with all four lamps burning and with each lamp shining separately was measured. An average intensity over the length of the slit was recorded at distances of 0, 1, 2, and 3 feet from the end of the light box. The process was repeated for slit sizes of 2, 1/2, and 1/4 inches. The results are tabulated in Table 7, and a plot of intensity in foot-candles versus distance from the end of the light box in feet using different slit sizes and four lamps shining is presented in Figure 16. The accuracy of the values of intensity as measured by the light meter is poor since each unit increase on the light meter scale caused the foot-candles of light intensity to be doubled. The values are given so that an approximation of the light intensity with each lamp burning and any combination of lamps burning would be known for distance from the light box extending to the bottom of the bank. It should be noted, however, that the intensity was measured in air and is somewhat higher than it would have been if it were measured in water.

Table 7. Light Intensity.

Light Number	Scale Number	Intensity in Foot-Candles	Distance from End of Box in Feet	Slit Size in Inches
1	14.5	160	0	0.25
	13.0	55	1	
	11.5	21	2	
	10.5	11	3	
2	17.5	1,250	0	
	15.5	305	1	
	14.0	110	2	
	13.5	78	3	
3	17.5	1,250	0	
	15.5	305	1	
	14.5	160	2	
	13.5	78	3	
4	17.0	880	0	
	15.0	220	1	
	14.0	110	2	
	13.0	55	3	
1,2,3,4	18.5	2,500	0	
	17.0	880	1	
	16.0	440	2	
	15.0	220	3	
1	15.5	305	0	0.50
	13.5	78	1	
	12.5	39	2	
	11.0	14	3	
2	17.5	1,250	0	
	16.5	640	1	
	15.5	305	2	
	14.5	160	3	
3	17.5	1,250	0	
	16.5	640	1	
	15.5	305	2	
	14.0	110	3	

(Continued)

Table 7. Light Intensity. (Continued)

Light Number	Scale Number	Intensity in Foot-Candles	Distance from End of Box in Feet	Slit Size in Inches
4	17.0	880	0	0.50
	16.0	440	1	
	15.0	220	2	
	14.0	110	3	
1,2,3,4	19.0	3,500	0	
	17.5	1,250	1	
	16.5	640	2	
	16.0	440	3	
1	17.0	880	0	2.00
	16.0	440	1	
	14.5	160	2	
	14.0	110	3	
2	18.0	1,750	0	
	17.5	1,250	1	
	16.5	640	2	
	16.0	440	3	
3	18.0	1,750	0	
	17.5	1,250	1	
	16.5	640	2	
	16.0	440	3	
4	17.5	1,250	1	2.0
	17.0	880	2	
	16.0	440	3	
	15.5	305	4	
1,2,3,4	19.5	4,700	0	
	18.5	2,500	1	
	18.0	1,750	2	
	17.0	880	3	

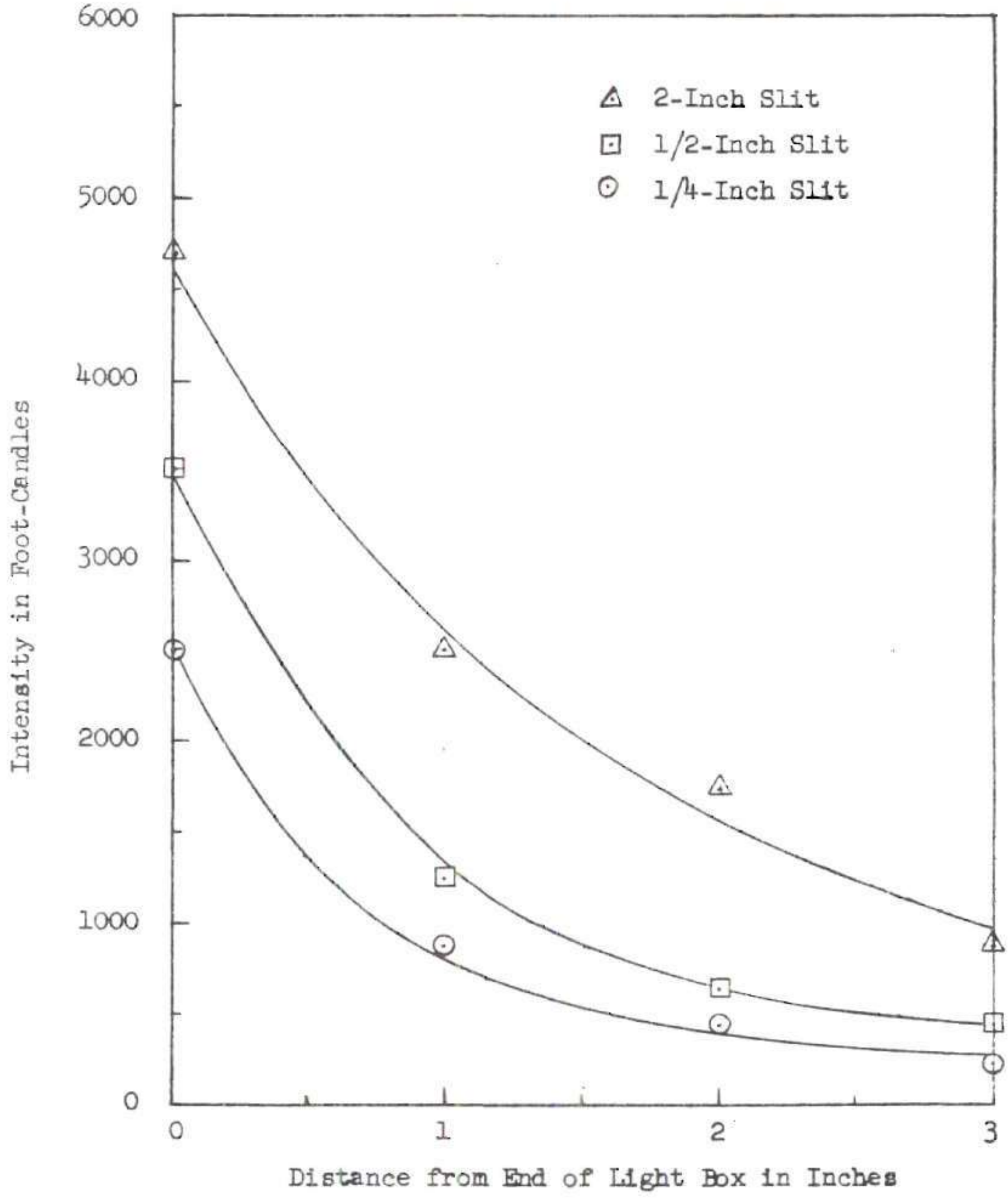

Figure 16. Light Intensity Produced by Four Lamps Versus Distance from Light Box.

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